Orbital Transfer Rocket Engine Technology Program
Integrated Control And Health Management

Phase II Task E.3 Final Report
Contract NAS 3-23772
NASA CR 182122
October 1988

Prepared For:
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

(NASA-CR-182122) INTEGRATED CONTROL AND HEALTH MANAGEMENT. ORBIT TRANSFER ROCKET ENGINE TECHNOLOGY PROGRAM Final Report (Aerojet TechSystems Co.) 139 p CSCL 21H

N89-11805

Unclas

G3/20 0169380

Aerojet
TechSystems
Company

October 1988

NASA CR-182122
ATC

INTEGRATED CONTROL AND HEALTH MANAGEMENT

PHASE II TASK FINAL REPORT

ORBIT TRANSFER ROCKET ENGINE TECHNOLOGY PROGRAM

Prepared For

National Aeronautics and Space Administration

By

Wilfried A. Holzmann and Warren R. Hayden

Areojet TechSystems Company

NASA Lewis Research Center
Contract NAS 3-23772

RPT/BB0820.4

FOREWORD

This document represents the final report to the National Aeronautics and Space Administration for work performed under Task Order E.3 to contract NAS 3-23772. The task work span was from June 1986 through May 1987. This task addressed the Integrated Control and Health Management (ICHM) technology requirements for the Orbit Transfer Rocket Engine Technology Program. This is a summary report in that all material discussed herein was presented to NASA program personnel at oral presentations or in the contractually required monthly progress reports during active work on the task.

The principal investigator, Dr. Joseph Yang, was unable to complete the report due to reassignment. The report authors assumed the report preparation task after the actual analysis effort was complete. The authors also wish to acknowledge the assistance of Edward M. Reich and Duncan D. MacGregor in the conduct of the ICHM task, in the oral presentations given during its course, and in review and comments during the report preparation.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF TABLES

LIST OF FIGURES

<u>LIST OF FIGURES</u> (cont.)

I. SUMMARY

When this engine control and health management task was approved engine designs for the Orbit Transfer Vehicle (OTV) had progressed to a point where a control assessment was necessary for confidence that the proposed expander cycle was practical. The oxygen and hydrogen turbopumps are mechanically separate, flow circuits are complicated, and numerous valves are required for these complex engines. Resources limited the scope of the work to developing a nonlinear dynamic model, but simulations with the model predict full range throttling, thrust, and mixture ratio control with the baseline engine controls. This success is an important validation of the engine design approach and encourages continued engine development. Additional work is needed, however, prior to full-scale engineering development to verify the linear dynamic model and to map the complete engine control range.

The second major task was to integrate the controls approach with a health management system. An integrated systems approach had been recommended by ATC and approved by the NASA as a means of reducing sensor numbers and data streams. The health management system also directly affects engine life and mission success, both important design considerations for the engine. It will also be used for pre- and post-flight health assessment. During the mission it will command the controller to prevent equipment damage or a catastrophic failure; very important functions for a piloted vehicle. The study produced a basic health management architecture fully integrated with the engine control function. Specific sensors were identified and simplified specifications developed for both sensors and the most import mechanical control elements, the valves. Enough of the groundwork has been completed to define the software development task that would make the system operational.

A major unknown in the integrated control and health management (ICHM) task was the amount of development work needed for the engine controller. This had been considered a $5 to 10M project based on the system complexity if a controller had to be specifically designed for this engine. Aerojet was able to verify that a new controller developed for pump-fed storable propellant engines could be modified to meet the OTV engine requirements. With a controller indentified all

I, Summary (cont.)

of the basic control and sensor hardware is either available or in the active development cycle. This assures that the ICHM requirements of the engine can be meet within any reasonable development schedule.

The next requirement for additional ICHM development will come in the preparation for a test bed or integrated component test program. Actual sensors and control valves will be used with software developed for a specific test site but representative of that needed for the engine controller. This report is the logical starting point for that phase of the engine development.

II. INTRODUCTION

A. BACKGROUND

1. Engine Control and Health Monitor Sensor Capability

Aerojet has investigated engine control requirements for the Orbit Transfer Vehicle Engine under NASA contracts going back to 1979 (NAS8-33574, see ref. 1). The present contract, however, departs from the former program direction by changing the emphasis from a strictly engine control investigation to an integration of engine control with engine health management. The health monitoring technology focus`of present NASA interest is in sensor development. Aerojet TechSystems Co. (ATC) shares this interest and believes that a comprehensive health management system is limited primarily by the availability of suitable sensors. Fortunately, much new sensor technology is being developed for automotive, industrial and aerospace applications. ATC believes that much of this new technology is applicable to rocket engines and can and should be adapted to programs such as OTV. The ATC approach to sensor development is to search out the best available technology for the specific application, modify and adapt it as required, and team with the most qualified vendor for its development.

2. Aerojet Approach to the ICHM Task

A summary chart of ATC's approach to the ICHM task is given in Figure 1. The NASA has accepted this approach to the extent that this preliminary ICHM task is largely concerned with the OTV engine control's development and modeling. With acceptable control analysis results obtained, the baselined control sensors can be used as a logical starting set for addressing health management sensor requirements. The necessary control and health management sensors have been identified, are listed in this report, and preliminary specifications have been prepared. In addition, ATC has investigated other aspects of sensor data use in the Orbit Transfer Vehicle as a means of deriving a basic design strategy for ICHM sensors that focuses on sensors having the greatest potential utility, not just those involving innovative sensing methods. Our basic design strategy is outlined in Figure 2. It is a conservative approach that is more concerned with extending the state-of-the-art rather than redefining it. The major benefits to be gained are high reliability and predictable sensor performance. A conservative approach to sensor

- ENGINE CONTROL MUST BE GIVEN FIRST PRIORITY DUE TO THE MISSION REQUIREMENTS AND UNIQUE DESIGN OF THE OTV ENGINE
  - ENGINE CONTROL IS A CRITICAL TECHNOLOGY THAT MUST BE VALIDATED FOR ANY NEW ENGINE
  - SYNCHRONIZED OPERATION OF MECHANICALLY SEPARATE TURBOPUMPS HAS BEEN DEMONSTRATED ONLY ON THE SSME
  - CONTROL REQUIREMENTS FOR THROTTLING OPERATION AND MANRATING ARE PARTICULARLY DEMANDING
  - DEFINITION OF CONTROL SENSORS IS A LOGICAL STARTING POINT FOR DEVELOPING SENSOR REQUIREMENTS FOR HEALTH MONITORING
- TRANSITION FROM ENGINE CONTROL VALIDATION TO SENSOR DEVELOPMENT
  - ATC CONSIDERS CONTROL STUDY RESULTS ACCEPTABLE BUT MORE WORK IS NEEDED
  - HEALTH MANAGEMENT SENSOR DEVELOMENT IS CURRENT PROGRAM INTEREST
  - CONTINUATION OF ENGINE CONTROL WORK SHOULD FOLLOW ENGINE PRELIMINARY DESIGN
- SENSOR DATA MUST SATISFY USER REQUIREMENTS
  1. ENGINE CONTROL - HIGHEST PRIORITY, GREATEST REDUNDANCY
  2. ENGINE HEALTH MONITORING - BOTH MISSION AND MAINTENANCE USE
  3. PILOT STATION DISPLAY - REAL TIME PROCESSED INFORMATION
  4. VEHICLE DATA TELEMETRY - REAL TIME DATA STREAM SELECTION
- DESIGN FOR COST EFFECTIVENESS
  - MULTIPLE USE OF SENSOR DATA WHEN POSSIBLE
  - CRITICAL SENSOR TASKS REQUIRE REDUNDANCY OR INDIRECT DATA DERIVATION FROM OTHER SENSORS
  - FMEA IDENTIFIES NEEDED SENSORS AND THE SENSOR RELIABILITY REQUIREMENTS
  - SENSOR COST CAN BE A SIGNIFICANT PART OF TOTAL ENGINE COSTS
  - NEW SENSORS CAN HAVE A DEVELOPMENT TIME MEASURED IN YEARS
  - SENSOR INTERFACE/POWER/DISPLAY REQUIREMENTS EFFECT ENGINE AND VEHICLE DESIGN

Figure 1. Aerojet's Approach to ICHM

- Use proven sensor designs when possible
- Miniaturize both electronics and transducers
- Consider that ruggedness and reliability tend to go together
- Require health management sensors for rotating parts
    - Vibration/out-of-balance indicators
    - Wear indicators
    - Seal failure indication
    - Rubbing/contact indicator for hydrostatic bearings
- Emphasize development of health management sensors used for maintenance decisions and system troubleshooting
    - Valve actuation rate sensing and recording
    - Leak and/or crack detection sensors
    - Temperature anomaly detection
    - Out-of-operating range excursions: temperature, mixture ratio, thrust, pressure sensing, recording and evaluating
- Sensors for operation record
    - Pc trace,flowmeter traces, turbine inlet temp. traces, engine compartment temp. trace, etc.
    - All data digitized and time correlated on recording

Figure 2. Basic Design Strategy for ICHM Sensors

development does not rule out innovation or free the development from challenges. Figure 3 is a summary of the challenges perceived in sensor development for the OTV engine. ATC expects to propose an ICHM task to the NASA that addresses the serious computational and processing needs arising from the immense quantity of sensor data that will be available. An application from the rapidly developing field of expert systems and other artificial intelligence (AI) techniques is one likely possibility.

3. Aerojet Dual Expander Engine Cycle

The ATC version of the OTV engine baselines a unique form of the expander cycle developed for high performance, turbopump-fed liquid propellant rocket engines. In a conventional hydrogen expander cycle the fuel is routed through the jacket of a regeneratively cooled engine where it acquires sufficient thermal energy to power the turbine drives of both fuel and oxidizer. The propellant then is routed to the injector and combustion chamber. This cycle is fairly simple and offers good performance potential. As all the propellant is burned in the combustion chamber there are no losses comparable to those from open cycles. Its limitations are related to dependence on only one working fluid. High chamber pressures (>1500 psia) require high (>1000°F) hydrogen exit temperatures from the regen chamber. This poses limits to materials and cycle life concerns. The hydrogen working fluid must also drive pumps for both fuel and oxidizer. This requires an interpropellant seal in the oxygen pump or a gear drive. There are also mixture ratio limitations and demanding design requirements for needed heat transfer within an acceptable chamber length.

The ATC dual expander cycle makes use of both fuel and oxidizer as working fluids. For the OTV engine the hydrogen fuel is used as the regen coolant for the combustion chamber jacket where it acquires sufficient energy to run the turbine driving the hydrogen turbopump before entering the injector. The engine concept used in the control study has an oxygen cooled nozzle extension with additional oxygen heating from a LO_2/GH_2 heat exchanger. The combined heat input raises the oxygen to 400°F. This is sufficient to drive the turbine on the oxygen turbopump but is considered a safe temperature for the turbine materials.

- CHARACTERIZE MOVING PARTS
  - RATES, NOT POSITION CHANGE ALONE
  - EXCURSION FROM SMOOTH, VIBRATION-FREE OPERATION
  - BEARING WEAR RATE AND LOCATION
  - UNUSUAL THERMAL GRADIENTS
- MINIATURIZATION WITHOUT FRAGILITY
  - SENSORS BUILT INTO THE PART
  - FORMED IN TO DAMAGE RESISTANT SHAPES (SHORT, THICK VS. LONG, THIN)
  - WIRELESS DESIGNS WITHIN A COMPONENT
  - USE OF EQUIPMENT GENERATED SIGNALS (PASSIVE TRANSDUCER ELEMENTS)
- REDUCE COST, WEIGHT, POWER REQUIREMENTS
  - TRADE REDUNDANCY AND RELIABILITY
  - USE AI TO DEVELOP INFORMATION FROM OPERATING SYSTEMS WHEN THERE IS A FAILURE OF SOME SENSORS
  - SIGNAL PROCESSING BY MICROELECTRONICS AT THE SENSOR SITE

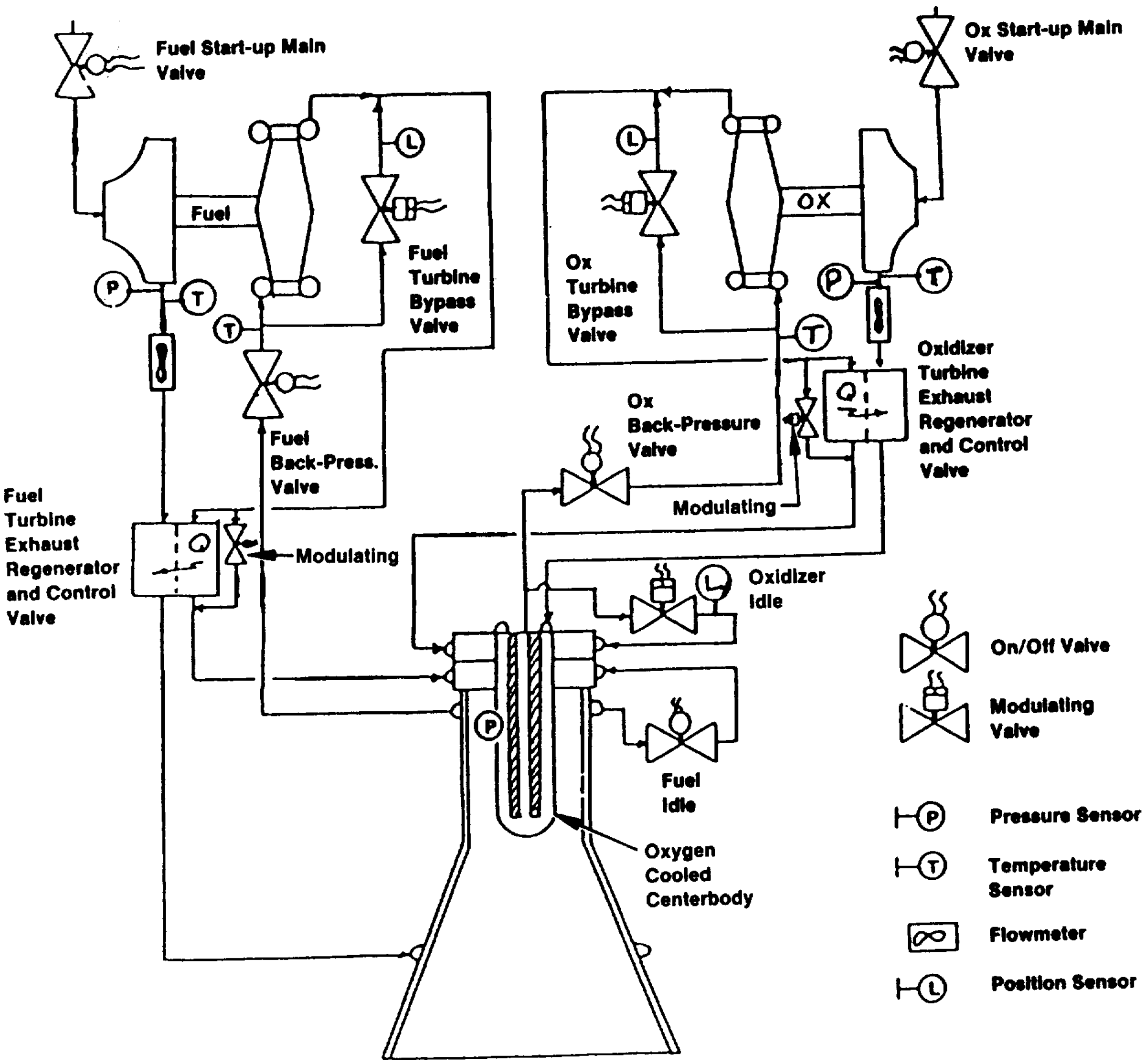
Figure 3. Sensor Development Challenges

By using both fuel and oxidizer as working fluids the dual expander cycle can deliver higher combustion chamber pressures at lower fluid temperatures than the conventional expander cycle. For throttling operation the mixture ratio limits are considerably broadened while maintaining close to optimum specific impulse. There is also a design and safety benefit from removing the need for an interpropellant seal from the oxygen turbopump. Of major importance at the system level is the capability to operate the engine without a helium purge system. This gives a major weight advantage to the cycle.

4. Dual Expander Cycle Engine Control

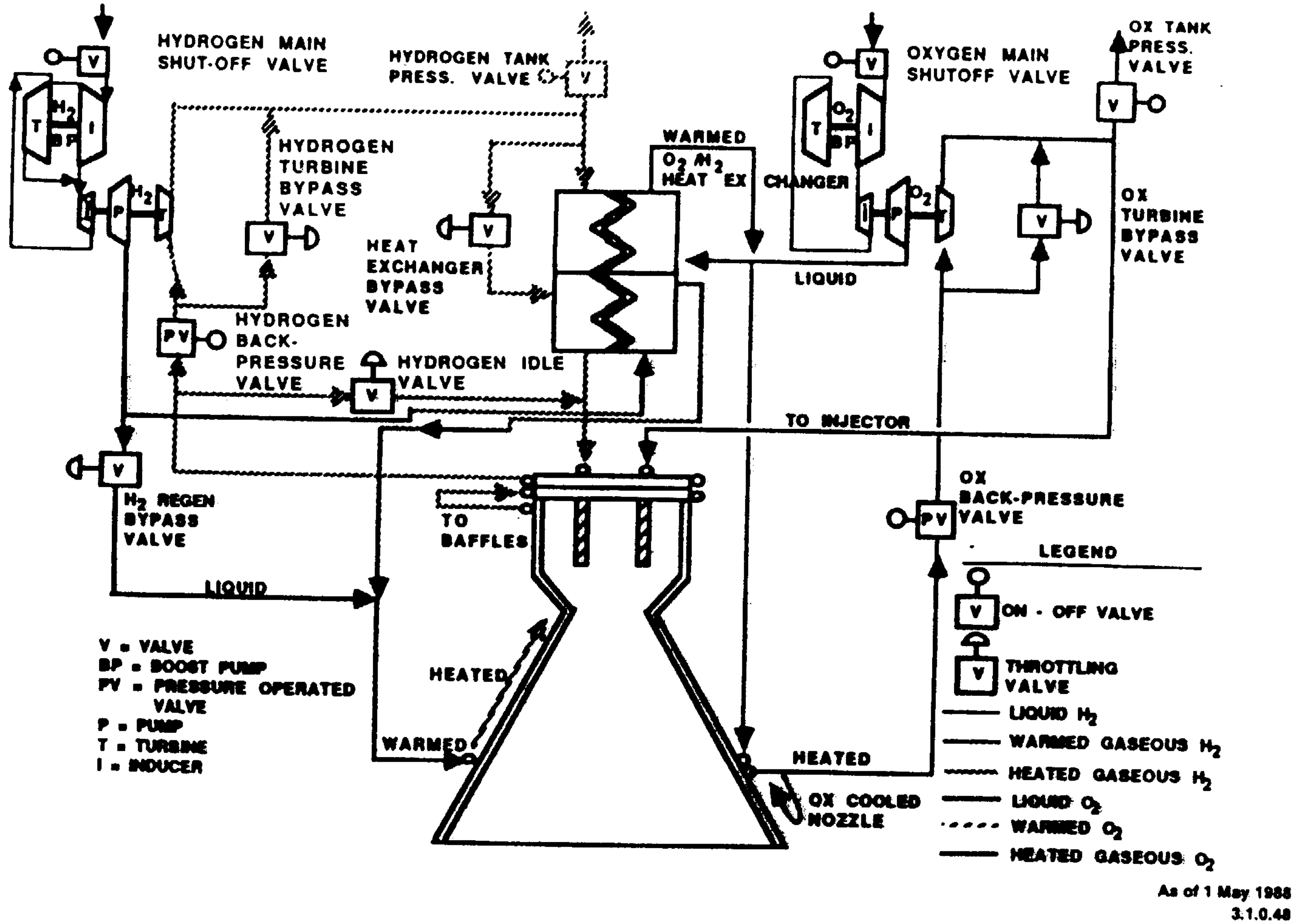
The OTV engine control schematic used for modeling is presented in Figure 4a. This control schematic was subsequently modified during the engine preliminary design task to the configuration shown in Figure 4b. Conceptually there is little difference between the two schematics but the changes in design details are substantial. The major change was to delete the oxygen cooled centerbody and provide oxygen heating by a LO_2/GH_2 heat exchanger and the regen cooled nozzle extension. Also added were boost pumps and provisions for autogenous tank pressurization. The major control concern is the mechanically separate turbopumps. Synchronization is absolutely dependent on sensor data properly interpreted and acted upon by the engine controller and control software. All engine operations are ultimately controlled by the 11 valves shown on the schematic in Figure 4b plus the two igniter valves. Valve control functions are listed in Table I along with the sensor data used to position the valves. The idle valve and back pressure valves are used only during startup and idle mode operation. The regenerator bypass valve and LO_2/GH_2 heat exchanger valve are used for working fluid temperature control. The turbine bypass valves control thrust and mixture ratio. All valve sequencing and positioning is done through an electronic controller or through line pressure actuation. The controller, in turn, receives all the relevant sensor input as well as operation commands. This engine has a degree of complexity beyond the limits for a mechanical start and operating procedure; a controller is necessary to its operation.

A direct spark ignition system was successfully tested in the ATC 3.0K lbf thrust TCA hot-fire test program. It is the baseline ignition system for the engine.



Nominal Thrust = 3000 lbf
Max. Thrust = 3750 lbs

Figure 4a. OTV Engine Control Schematic



Nominal Thrust = 7500 lbf
Max. Thrust = 8625 lbs

Figure 4b. OTV Engine Dual Expander Cycle

TABLE I

OTV-ENGINE VALVES AND SENSORS FOR ENGINE CONTROL

Valve Name	Abbreviation	Control Function	Primary Sensor Data Source
Hydrogen Turbine Bypass	HTBV	Mixture Ratio	Hydrogen, Oxygen Flowmeters, Chamber Pressure
Oxygen Turbine Bypass	OTBV	Thrust Flowmeters	Oxygen Flowmeters, Hydrogen
Heat Exchange Bypass	HEB	Oxygen Max. Temperature	Oxygen Turbine Inlet Temperature
Hydrogen Regenerator Bypass	HRBV	Hydrogen Max. Temperature	Hydrogen Turbine Inlet Temperature
Hydrogen Idle	HIV	Idle Mode Start	Flowmeter Data, Chamber Pressure
Hydrogen Back Pressure	HBPV	Start Pressure Balance	Line Pressure Operated
Oxygen Back Pressure	OBPV	Start Pressure Balance	Line Pressure Operated
Hydrogen Main Shutoff	HMSV	Propellant Isolation	Commanded by OTV Pilot (Engine Start, Stop) or Engine Controller
Oxygen Main Shutoff	OMSV	Propellant Isolation	Commanded by OTV Pilot (Engine Start, Stop), or Engine Controller
Hydrogen Igniter Control	HICV	Engine Start	Chamber Pressure
Oxygen Igniter Control	OICV	Engine Start	Chamber Pressure
Oxygen Tank Pressurization	OTPV	Tank Pressurization	Tank Pressure, Chamber Pressure
Hydrogen Tank Pressurization	HTPV	Tank Pressurization	Tank Pressure, Chamber Pressure

II, Introduction (cont.)

B. SCOPE

1. Task Order Scope Definition

Provide the necessary personnel and support to continue the technology development of a health management system for this OTV engine concept. Build on earlier work to improve the engine system model, evaluate the control logic, specify and determine the availability of control components and sensors, and integrate health management into the control system.

2. Specific Subtasks

Subtask I - Engine System Modeling

Continue engine system dynamic modeling using the baseline engine system developed under previous contract efforts. An approach is to compile an initial model from simplified models of the primary engine components (i.e., TPAs, thermal and combustion processes and control elements). Engine model sophistication is increased by including more detail for the individual component models.

Update engine models, both dynamic and steady-state, as hardware test data becomes available or as control system changes are identified in Subtask II.

Subtask II - Control Logic Evaluation

Evaluate the preliminary control logic identified in earlier contract work using the engine system dynamic models developed in Subtask I. Perform control system stability analyses and determine system gains and shaping filter requirements for a stable, responsive system. Perform a controllability analysis to determine the engine and control system response during transient conditions such as start-up, shut-down and throttling.

Modify the control logic as necessary to achieve the desired system performance. Change the baseline control system if satisfactory performance cannot be achieved by adjusting the control logic algorithms.

Subtask III - Control Element Requirements

Establish control element requirements. Determine control valve parameters such as flow areas, resolution, accuracy, actuation method, valve type and operating environment. Identify control sensors required to implement the control system logic identified in Subtask II. Preliminary requirements for these sensors will be established. Determine basic engine controller requirements such as sensor processing, valve output drive capability, and computation and memory needs. For each of the control elements required to operate the engine, assess current and/or future component availability.

Subtask IV - Health Monitoring

Evaluate the baseline control system design so that an integrated control and health management design approach can be achieved. Key areas to be considered include sensors, computational requirements and algorithms. Emphasis is to be placed on the degree of health management that can be achieved using the control system sensors identified in Subtask III. Document the set of sensors, the parameters sensed or synthesized from this set, and the algorithms for synthesizing these parameters. The benefits of additional sensors to enhance health monitoring capabilities shall be considered. Review of prime contractor OTV studies so that the requirements for space-based repair/maintenance, modularity or other appropriate factors, such as life cycle cost, are accounted for in the health monitor design.

III. ENGINE SYSTEM MODELING

A. CONTROL REQUIREMENTS

A throttling range of 10:1 and mixture ratio variation of 5.0 to 7.0 over this range has been specified for the OTV engine. The nominal operating design point assumes a thrust of 7500 lbf and mixture ratio of 6.0. A dual expander engine cycle has the capability of meeting the throttling requirements within the limitations of the mixture ratio range. This is important in maintaining near optimal specific impulse from minimum to maximum thrust. A list of engine requirements is given in Table II.

B. CONTROL VALVES USED IN THE ENGINE MODEL

Several control valve configurations were investigated in previous studies in order to determine their effect on engine control. This was achieved by using power balance models to determine the sensitivity of engine thrust and mixture ratio to valve perturbations. The in-line throttling concepts were determined to be unsuitable as they exhibited practically no control over mixture ratio. Analytical results showed that bypass valves at the oxidizer and fuel turbines are effective in meeting the control objectives. Thrust control is provided by simultaneous modulation of the oxygen and hydrogen turbine bypass valves. Mixture ratio adjustments are made using the hydrogen turbine bypass valve. One of the important functions of the controller is to maintain stable engine operation. This would be impossible to achieve in an open-loop system due to the coupling between thrust and mixture ratio.

C. MODEL BUILDING

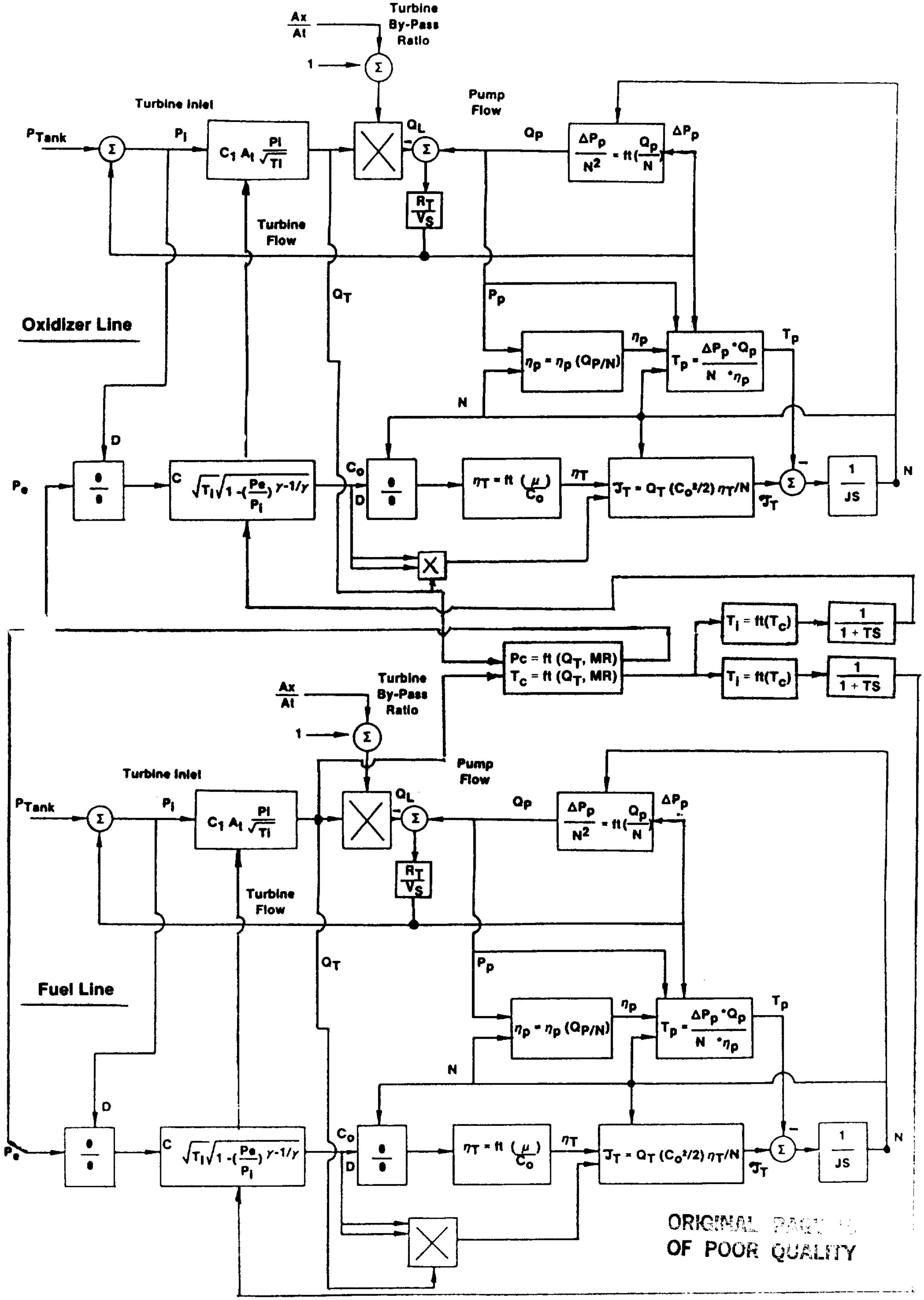
1. Dynamics Simulation Model

The dynamics model shown in Figure 5 was used to study the transient behavior of the engine system. TUTSIM©, a dynamics simulation package, was implemented for the actual model coding and simulation work. TUTSIM© is an acronym based on Twente University of Technology Simulation Software. It is a product of the software firm Applied I of Palo Alto, California. It was designed for use on the IBM PC/XT/AT/Jr computers. A number of configurations are available

© = Copyright Cymbol

Table II
OTV Engine Design Drivers

Driver	Measure of Merit	Goal/Requirement
1. Performance	Specific Impulse	490 Seconds
2. Weight	Dry Weight of Deliverable Eng	180 lbm
3. Cycle Life	#Starts, Hours of Operation, Hot Gas Side Wall Temp., Operating Envelope	100 Starts, 4 Hours Service 500 Starts, 20 Hours Operational Life
4. Gimbal	Pitch & Yaw Movement, Weight, Envelope	± 20 Degrees
5. Packaging	Engine Length with Nozzle Stowed, Vehicle Interface	TBD, Assume 60 Inches
6. Combustion Stability	Steady State Thrust Variation, Percent Over Operating Range	Not Specified
7. Thrust	#Elements, Thrust/Element, Chamber Diameter	7500 lbf
8. Throttling Range	Nominal Thurst, Minimal Thrust, Control Complexity, Added Components	10:1
9. Space Based	Vacuum Operation, No Purge Gas Required	No Change to Service Life
10. Man-Rated	Reliability #, Confidence Level, Control Complexity, Valve Design	Fail Operational, Fail Safe
11. Tank-Head Start	Reliable Starting on Tank Pressure	NPSH: 15 ft-lbf/lbm for H_2 2 ft-lbf/lbm for O_2
12. Autogenous Pressurization	TPA Output Sufficient to Pressurize Propellant Tanks above Cavitation Minimum Pressure	TBD, Assume 25 psia, ± 5 psi



ORIGINAL PAGE IS OF POOR QUALITY

Figure 5. Engine Dynamic Simulation

including a professional form for modeling large systems and for control and servo design. It allows for 999 blocks per model. Graphic support is required. This can be an IBM Color Graphics Board with color or NTS monochrome CRT, a Hercules High Resolution Graphics Board, an IBM EGA board in the default CGB mode, an IBM Dot Matrix PC and Epson Printers, or any other printer that will work with the IBM "Graphics" DOS command.

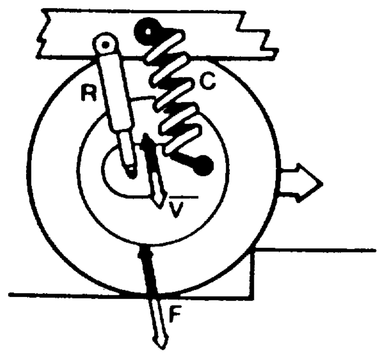
The TUTSIM© program is designed for the simulation of continuous dynamic systems. The key to use of the program is the preparation of the TUTSIM block diagrams. A problem is defined, mathematical models developed, a block model is composed based on the mathematical model, and the program presents results graphically. This is shown in Figure 6. Model parameters are easily entered and changed. Results are available in graphical display or numerical tables on the screen or as hard copy.

The program originated at Twente University of Technology in the Netherlands. Development has continued over 14 years with users now found worldwide. The core of TUTSIM is written in assembly language allowing for the fastest possible program execution. Non-linears, discontinuous, and special mathematical blocks add to its versatility. It is designed to be highly interactive allowing simulation interrupt with changes to parameters or output directives. TUTSIM can be called from other programs, modified, and re-run to optimize a parameter or for special analysis. The simulation algorithm allows the user to specify the delta time steps of the simulation. The entire model is "solved" at each delta time step. With well chosen time steps the solutions will closely approximate a continuous solution.

Program limitations are largely those of the personal computers in terms of speed and memory. The mathematical algorithms must be realistic, however, if the results are to be if any valve. During the control modeling algorithm preparation was by far the most exacting and tedious task. Once the model was developed the program ran well.

Frequency domain analysis techniques are not included in this software. The two basic state equations of the model are derived from a summation of torques at the fuel and oxidizer turbopump assemblies. The angular acceleration

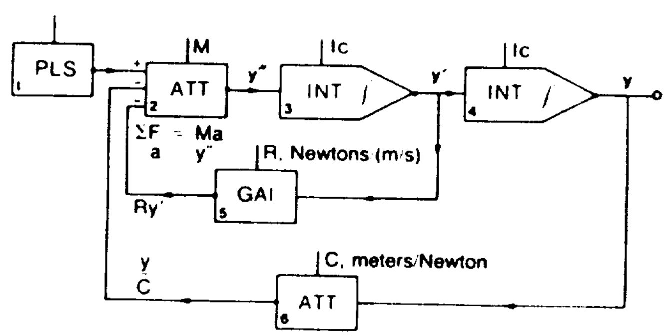
Problem:



Mathematical Model:

$$y'' = \frac{1}{M}\left(F - Ry' - \frac{1}{C}y\right)$$

Block Model:



Results:

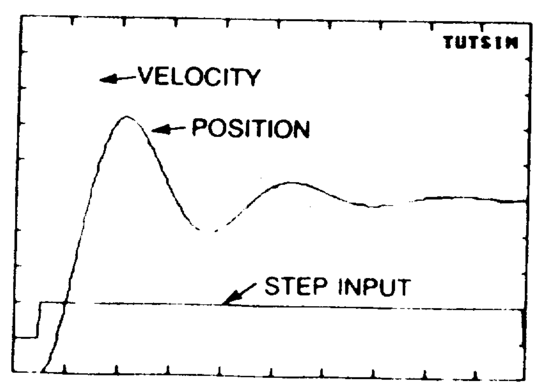


Figure 6. Tutsim Program Application

of the turbopump (TPA) shaft is obtained from the difference in turbine and pump torques divided by the inertia of the TPA. Additional states in the model relate to the average pressure between the pump discharge and turbine inlet for both the oxidizer and fuel circuits. These particular state equations account for the capacitance of the system. Phase lags between the combustion chamber temperature and turbine inlet temperatures were also incorporated to simulate the effect of thermal capacitance. A list of symbols is given in Table III.

2. Engine Component Modeling

The engine response during start-up and shut-down was obtained by combining the previously described turbopump dynamics model with a specified control configuration. Figure 7 illustrates the interrelationship between the two systems. The inputs are thrust and engine mixture ratio. These inputs are used to determine the required fuel and oxidizer flow rates. The turbine bypass valve schedule blocks represent table look-ups of the turbine bypass valve positions. Power balance runs at specified operating points through the throttling range were used to generate the bypass valve schedules (refer to Figure 8).

D. START MODES/THROTTLING

1. Tank Head Start

Requirements for the OTV engine include a capability for successful starts at tank pressures equivalent to the vapor pressure of hydrogen at 37.8•R and oxygen at 162.7•R. This is approximately 20 psia and 15 psia, respectively. On start the engine chamber is effectively at vacuum. The unaided maximum pressure differential available for start, then, is 15 psia which is set by the oxygen circuit. All line and component pressure drops must be accommodated within this pressure differential less a small combustion chamber pressure. This is a very small driving force for a rocket engine and poses a number of problems which are discussed below.

a. Pressure Fluctuations From Propellant Boiling. The engines are very likely at a temperature of 200 to 300°R higher than the entering propellant. Lines, turbopumps, and valves must be chilled to the same temperature as the propellant before pressure fluctuations from boiling propellants subside. During their

Table III
Symbols Used in the Simulation and Control Models

Symbols Used in Figure 11 and Table IV

Q_P - Pump Flow
N - Pump Speed
ΔP_P - Pump Pressure
τ_T - Turbine Torque
J - Turbo-pump Inertia
X_y - Valve Position of Pump Pre-Valve
C, A_t - Turbine Throat Equivalent Area
T_i - Turbine Inlet Temperature
η_P - Pump Efficiency
τ_P - Pump Torque
Co - Turbine Spouting Velocity
η_t - Turbine Efficiency
- Turbine Gas Specific Heat Ratio
P_c - Chamber Pressure
P_T - Turbine Inlet Pressure

Symbols Used in Figure 5

P_e - Turbine Exit Pressure
μ - Mean Turbine Blade Speed
MR - Engine Mixture Ratio
T_c - Combustion Temperature

Symbols Used in Figure 19

U_{cone} (t) - Commanded Actuator Positions
U (t) - Actrual Acutator Positions
U_m (t) - Measured Actuator Positions (Inlcues Sensor Noise)
Z (t) - System Control Variables (e.g., Chamber Pressure, Turbine Speed, etc.)
Z_m (t) - Measured Control Variables
Z (t) - Estimated Control Variables
F - System Matrix
G - Control Matrix
H - Output Matrix
D - Control Output Matrix

Table III
Symbols Used in the Simulation and Control Models (Cont)

Symbols Used in Figure 7

M_f	-	Mass Flowrate of Fuel
M_o	-	Mass Flowrate of Oxidizer
SV	-	Sliding Valve Actuation (Proportional Valve)
X_v	-	Vavle Position
$(X_v)_R$	-	Alogorithm for Vavle Positioning
$(M_o)_R$	-	Algorithm for Turbine Bypass Vavle Positioning Based on Oxidizer Mass Flowrate
$(M_f)_R$	-	Alogorithm for Turbine Bypass Vavle Positioning Based on Fuel Mass Flowrate
N	-	Feedback Signal from Oxidizer or Fuel Flow Used for Closed Loop Control of Turbopumps or MR
D	-	Feedback Signal from Fuel Flow Used for Closed Loop Control of Mixture Ratio

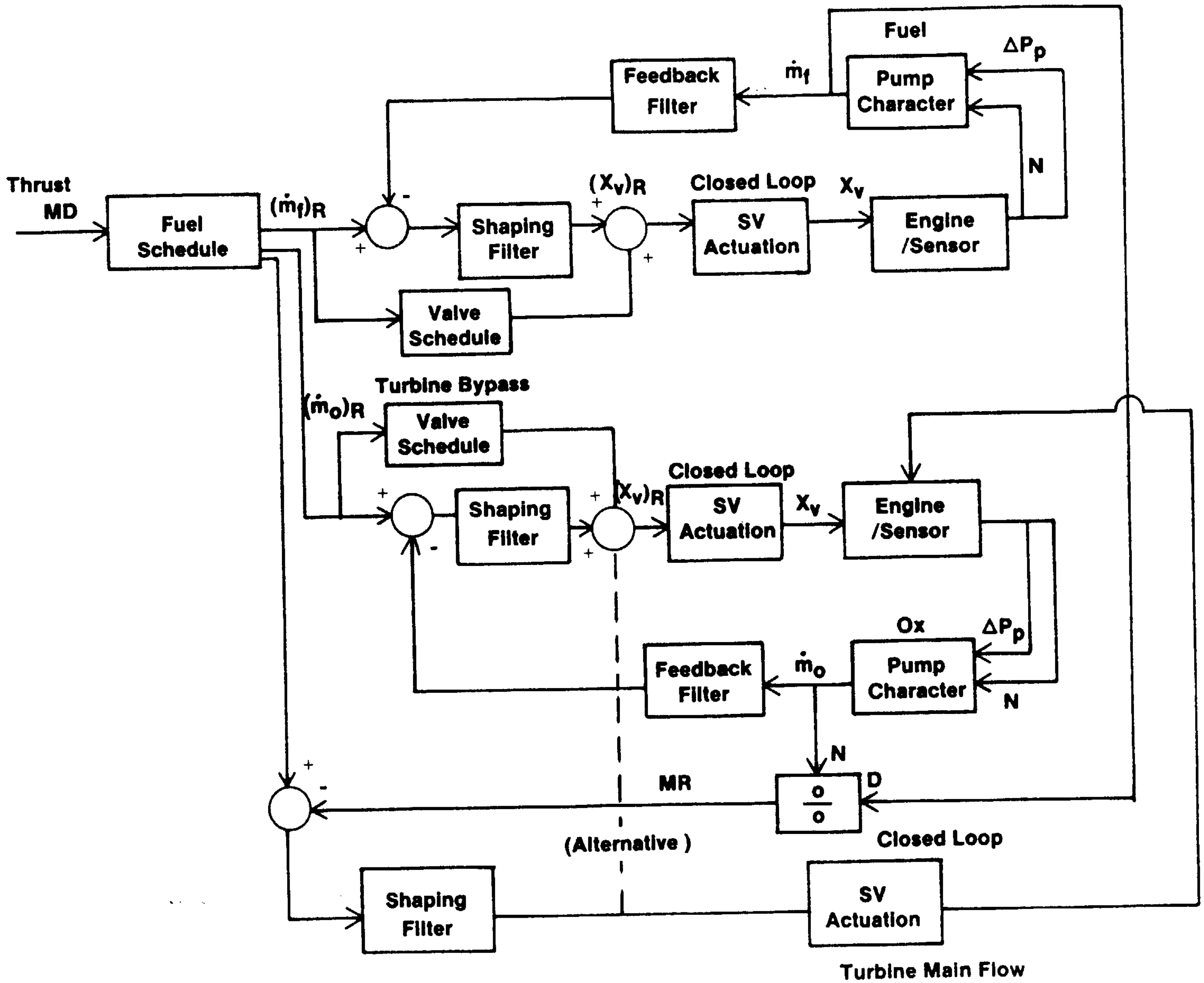


Figure 7. OTV Engine Control Configuration

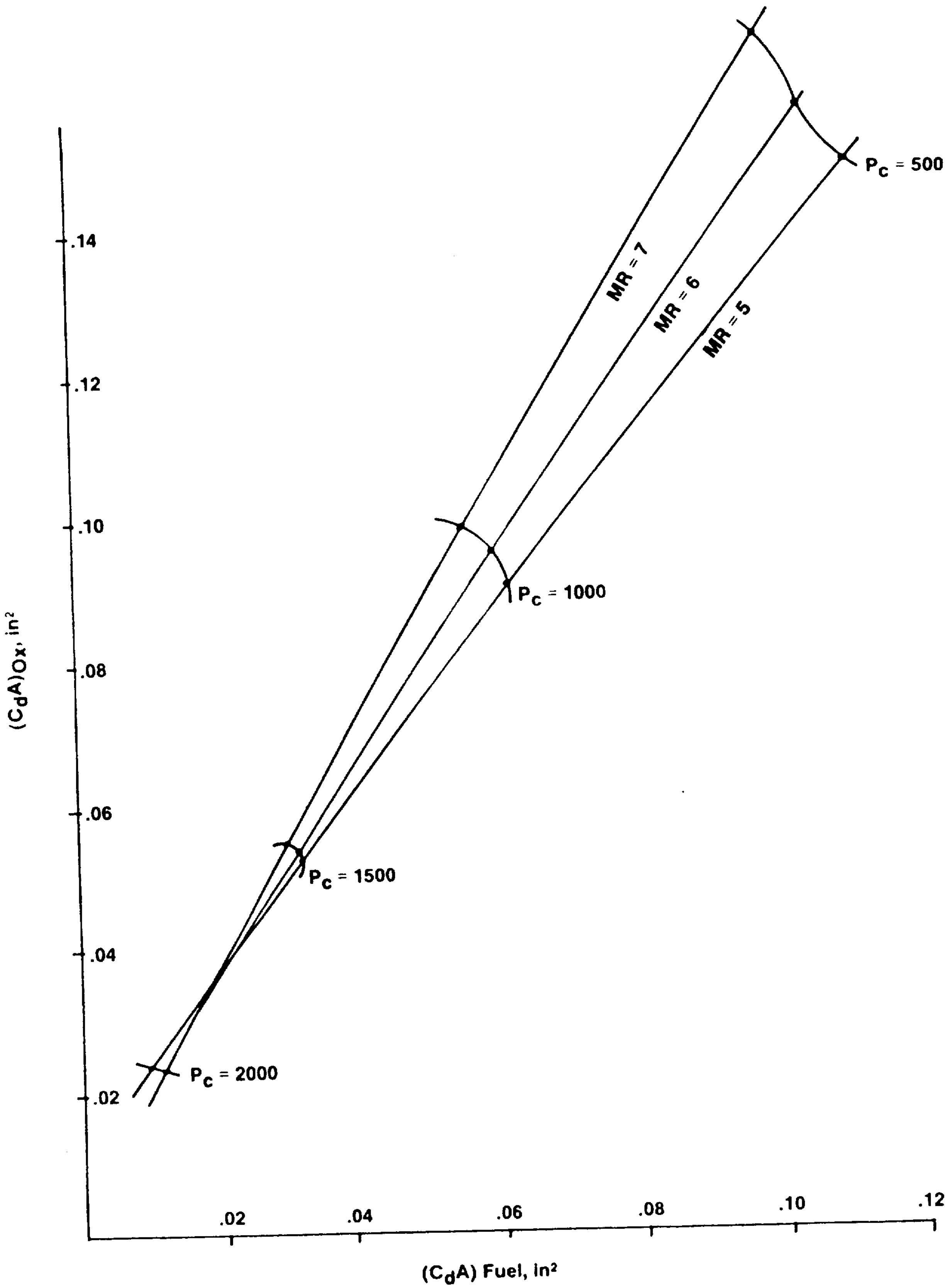


Figure 8. Turbine Bypass Valve Fuel Schedule

chilldown period flowrates and pressures will be erratic within the flow circuits. A start at this time could be characterized by rapid chamber pressure fluctuations, uncontrollable mixture ratio changes, and intermittent loss of flame with subsequent re-ignitions and pressure spikes. Such operation must be avoided. One means is to dump a specific amount of the propellants through the engine without ignition. This can cost several hundred pounds of propellant to achieve chilldown. Another option is to recirculate the chilldown propellants back to the tanks through recirculation loops. For such loops to work, however, there must be a recirculation pump in each circuit. The obvious choice is a small electrically driven pump located near the propellant tank outlet. It does not have to have a flow capacity of more than 10% of the full-thrust flowrate. With such a pump chilldown will be rapidly completed with little or no loss in propellant. A bonus is rapid tank pressurization from the returning propellant due to heat pickup from the engine and propellant conversion to the gas phase.

The recirculation loop also requires added engine valves and lines to prevent the propellant from entering the injector during chilldown. The recirculation pumps can be continued in operation during the start to add a very useful boost in pressure to the engine. Once pumped idle is reached so that the autogenous pressurization system is operational they would be turned off.

A compromise start/chilldown procedure would use some initial propellant dumping with ignition started just as soon as sensor data indicated stable pressures and temperatures at the turbopumps.

b. <u>Susceptibility to Combustion Transients</u>. Combustion adds additional pressure fluctuations that, at low feed pressures, can be coupled to the feed system dynamics as a chug instability. This can be severe enough to damage equipment or couple with the vehicle dynamics to effect the whole vehicle as a pogo instability. The recourse is an immediate shutdown. Avoidance is best done by a rapid acceleration through the potential chug range to a stable engine operating point. We do not expect a prolonged period of operation at tank head idle for this engine; the available pressure drops are not high enough to preclude chug despite the expected smooth combustion with the proposed injector elements.

c. Intermittent Combustion. The very low tank pressure requires a very low combustion chamber pressure for sustained operation. One concern is that the pressure spikes on lightoff may be high enough to stop propellant flow from one of the circuits. At that time the flame would extinguish only to be followed by another lightoff and pressure spike. This would be evident as a rapid popping that could be of increasing or decreasing magnitude. Continuous ignition during start would lessen the possibility of popping, but not entirely eliminate it. A better solution is to increase the system pressure to a value above the lightoff pressure spike.

d. Lack of Repeatability From Start-to-Start. A highly repeatable start transient is very useful in mission planning. With a tank head start there will be some unavoidable variability between starts. This can be avoided by compressing the time between lightoff and reaching a stable operating point. Prolonged operation at tank head idle would be characterized by large variations in delivered impulse for a given operating time. Such variations may be acceptable if they can be calculated in real-time.

e. Control Elements for Tank Head Start. A successful tank head start will require low pressure drop flow circuits. The engine schematic in Figure 4 shows a fuel idle valve. This valve opens on start to bypass the hydrogen turbopump circuit for a low pressure drop propellant route to the injector. As combustion stabilizes and more propellant flows through the TPA circuit the idle valve can be closed. Mixture ratio is controlled by the modulation of the variable position fuel idle valve.

f. Two Engine Thrust Vector Control. With side-by-side mounting of the two OTV engines the vehicle center of mass should be on a line between the two engines. Any difference in thrust between the two engines during start must be corrected by a gimbal movement of one or both engines or by firing of an attitude control thruster. Smoother operation will result if the start transient on both engines is very nearly identical and characterized by a rapid increase to a stable operating point.

2. Pumped Idle Mode

Pumped idle is defined as engine operation where the turbine power is sufficient to overcome the tare torque of the TPA. It represents minimum thrust operation with active turbomachinery. Up to that time the engine operating temperature and chamber pressure are relatively low since chamber pressure cannot exceed tank pressure minus system pressure drops. When the TPAs begin to rotate the propellant pressure in the engine system is no longer limited by tank pressure. As an operating point, pumped idle would be somewhat above the start rotation condition so that system fluctuations would not stall the pumps.

a. Control in Pumped Idle. At pumped idle the fuel idle valve is closed, and all propellant flows through the TPA circuits. The pressure operated back-pressure valves are functioning as high pressure drop flow restrictors (they never completely shut off flow and open completely when chamber pressure reaches 500 psia ±50 P psia). The hydrogen regenerator bypass and HGX bypass valves will be at 90% bypass (a margin of 10% is required for control authority) to control bulk temperature rise and chamber maximum wall temperature. The turbine bypass valves will be very nearly in the maximum bypass position but modulating for thrust and mixture ratio control.

The stability of this mode is highly dependent on control range (i.e., valve position range and flowmeter accuracy) and the tare torque differences between the two mechanically separate turbopumps. The two pumps must begin rotation at very nearly the same time; otherwise, there is a risk that the rapidly increasing output from the rotating pump will cause a mixture ratio change beyond the control of the bypass valves. This mode is very difficult to model accurately without actual pump tare torque and performance data.

3. Engine Throttling.

The 10:1 throttling requirement is considered as a capability for fully controlled engine operation from 750 lbf thrust to 7500 lbs thrust at some mixture ratio between 5.0 and 7.0. There is no stated requirement for a specific rate-change in thrust although this is an important consideration in the controls design and there

will be a practical rate limit. Relatively slow changes assure close control of mixture ratio.

a. Throttling Applications. There are three likely mission scenarios where throttling is needed or useful:

1) Landing a vehicle on the moon or Mars.

2) A gradual reduction in thrust during propellant depletion to control G-loads on payloads sensitive to acceleration forces.

3) Operation at lower than rated thrust to accomplish a precise orbit adjustment maneuver or rendezvous.

The first application will be the most demanding. If the engine control system can respond adequately to the moon lander mission needs, the other missions will be within the design envelope.

b. Throttling Control. Throttling is done primarily by commanding the oxygen turbine bypass valve to a specific position with the hydrogen bypass valve adjusting as needed to keep within the mixture ratio range. During throttle down operation the hydrogen regenerator bypass valve will allow more bypass due to the hydrogen bulk temperature rise through the chamber. The oxygen regenerator bypass valve would also increase the bypass based on the reduced power requirement of the ox TPA. The principal valves used during throttling, however, are the turbine bypass valves. Their action has been modeled and is given in Figure 9. The non-linear oxygen bypass prediction at low chamber pressures is due to the actuation of the back pressure valve. This non-linear operating regime will require a different control algorithm for reliable operation. One possibility is the use of TPA speed to calculate oxygen flow at chamber pressures below 600 psia to compensate for nonlinearities in flowmeters and the oxygen turbine bypass valve.

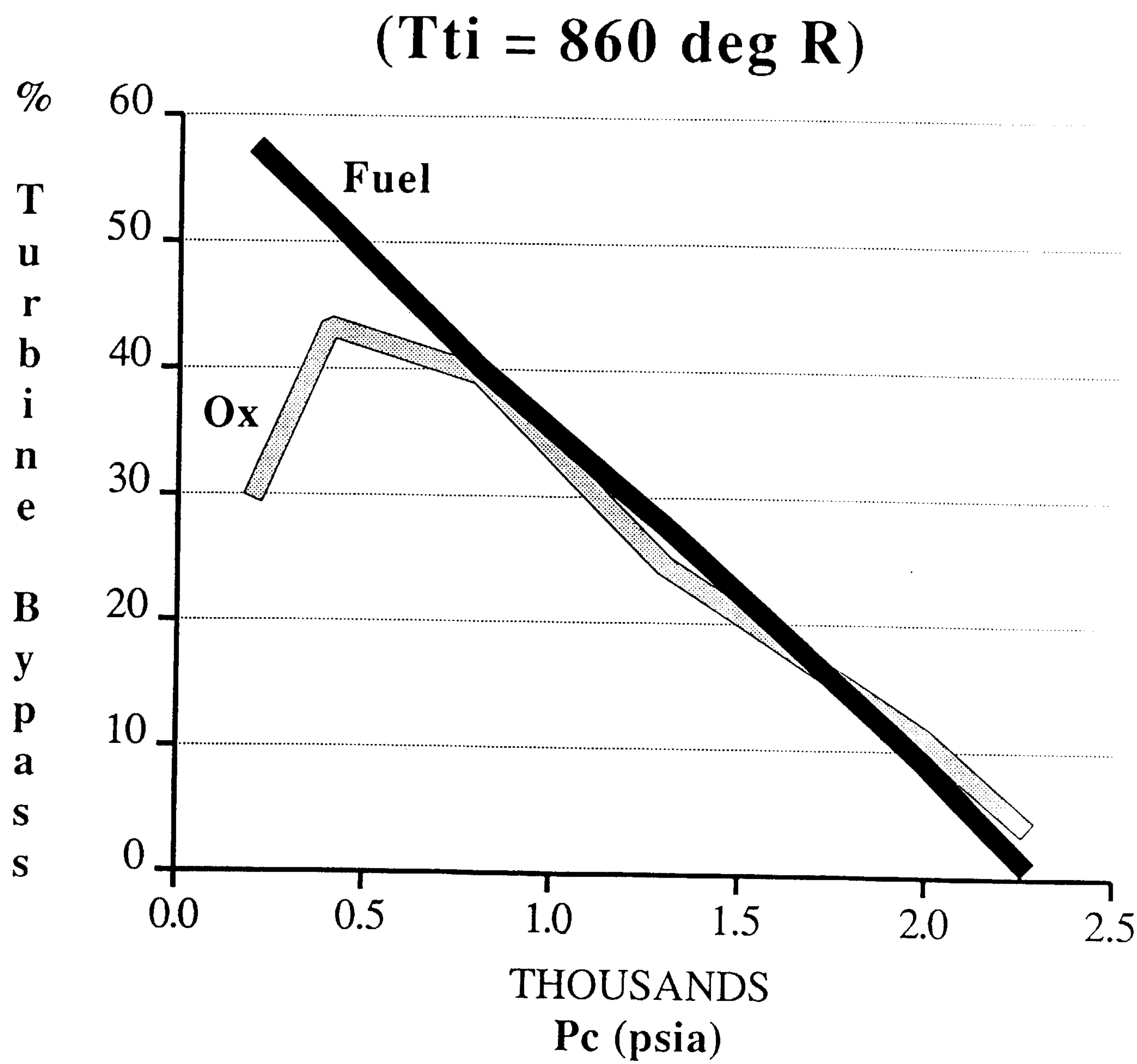


Figure 9. OTV Engine Turbine Bypass Percent vs. Chamber Pressure

IV. CONTROL LOGIC EVALUATION

A. SYSTEM GAINS AND SHAPING FILTERS

For an uncompensated system there will always be an error between commanded thrust/mixture ratio and actual thrust/mixture ratio. This is due to such factors as general system disturbances and limitations in mathematical modeling used for valve scheduling calculations. To overcome this difficulty a feedback compensation configuration is utilized. The shaping filters and feedback gains are designed to provide adequate system stability and response times with no steady state error. For the model depicted in Figure 7 the shaping filters were assumed to be of the proportional plus integral type and the feedback filters were set as unity gains. The dynamic simulation results shown in Figures 10 and 11 were derived using the closed-loop model. From these results it can be seen that the system remains stable for changes in the command input signal. The simulation results, however, do not provide any information as to the overall stability of the system.

B. CONTROL SYSTEM STABILITY ANALYSIS

In order to determine the phase and gain margins, the system must first be linearized about an operating point. Once this has been accomplished, the overall linear transfer function between input and output is used to calculate the stability margins. In performing the linearization for this application, the fuel and oxidizer circuits were treated independently. Figure 12 shows the linearized propellant circuit equations. The partial derivative terms used in linearizing the torque expressions are given in Table IV. Analysis was started for determining system stability at the nominal thrust level. Additional work is still required to tune the system such that results from both the linear and nonlinear models match. Further analysis will be required to verify system stability through the entire throttling range. This can only be accomplished by identifying a number of discrete operating points spanning the dynamic range. For each operating point the partial derivative terms given in Table IV are evaluated. These values are then substituted into the linearized system transfer function. Model reduction techniques are used to simplify the transfer function so that frequency analysis methods may be utilized to determine the phase and gain margins.

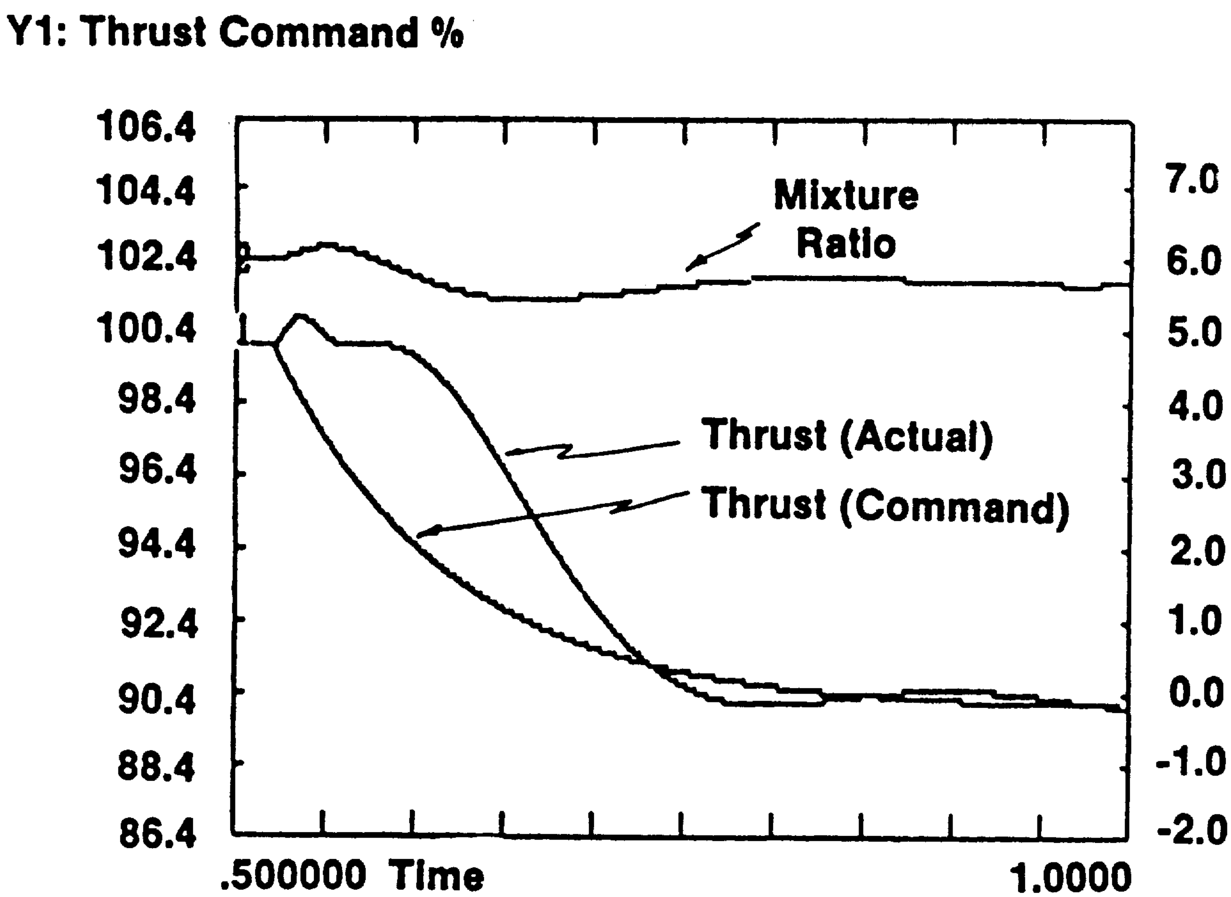


Figure 10. Predicted Response to 10% Throttle Down Command

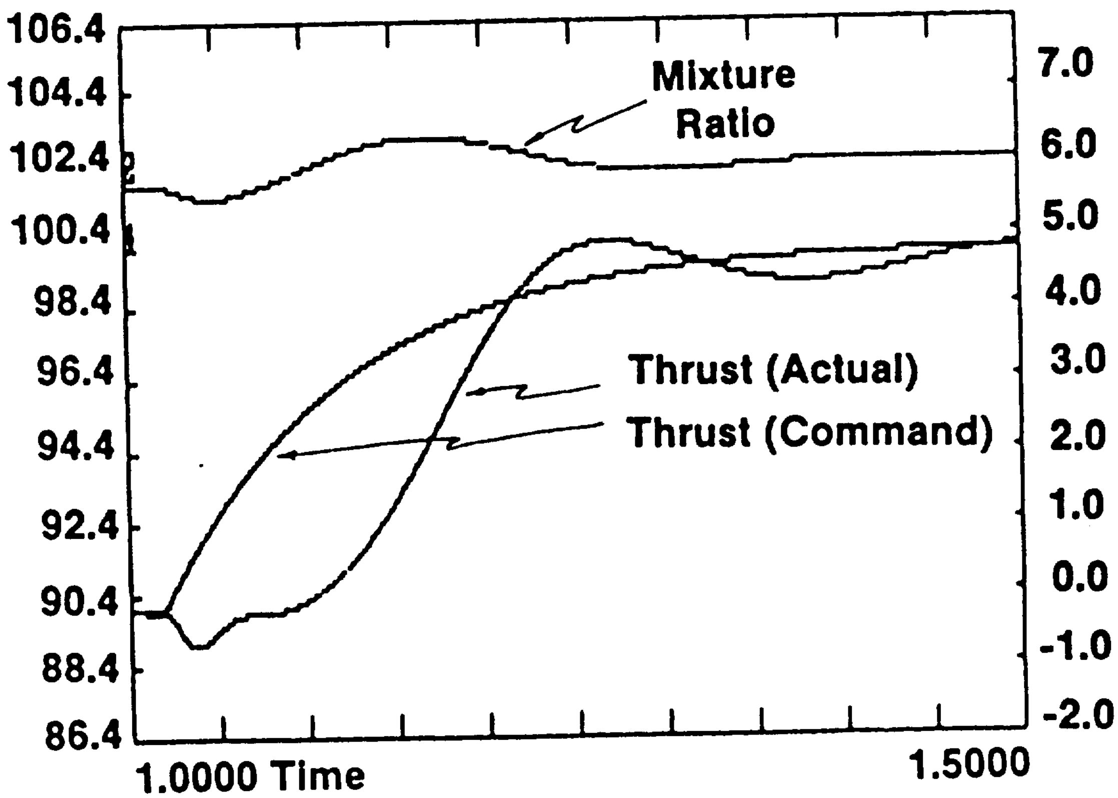
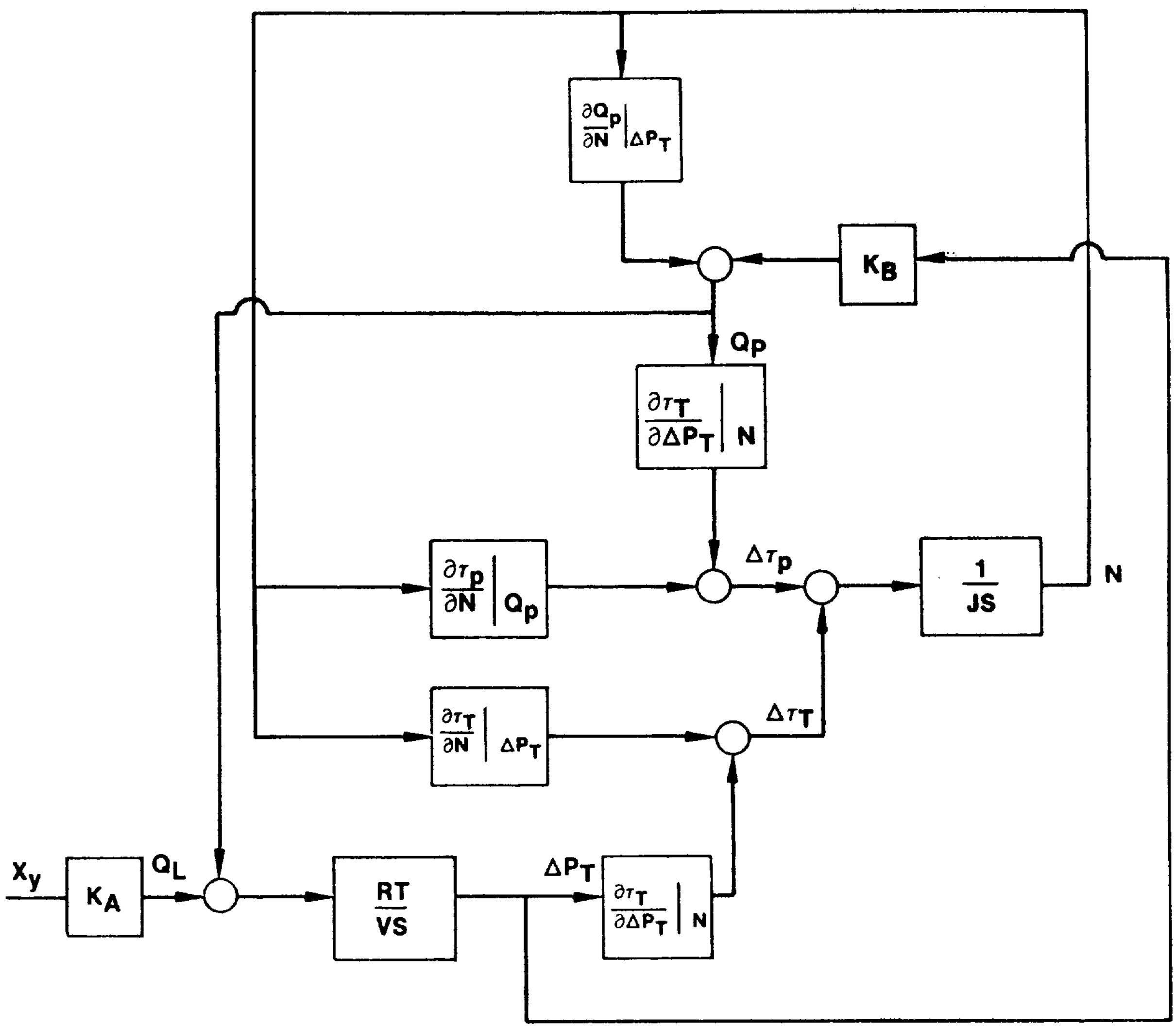


Figure 11. Predicted Response to 10% Throttle Up Command



Refer to Table III for Definition of Symbols

Figure 12. OTV Engine Linear Dynamic Model

Table IV
Parameters in the Engine Linear Dynamic Model

$$\frac{\partial Q}{\partial X} = \frac{\dfrac{Q_p\sqrt{T_i}}{(1+x)^2 C_1 A_t}}{\dfrac{\sqrt{T_i}}{(1+x)\,C_1 A_t} - N\dfrac{\partial\, ft\left(\frac{\Delta P_p}{N^2}\right)}{\partial\left(\frac{Q_p}{N}\right)}}$$

$$\frac{\partial Q}{\partial N} = \frac{2\,N\,ft\left(\frac{Q_p}{N}\right) - Q_p\dfrac{\partial\, ft\left(\frac{\Delta P_p}{N_2}\right)}{\partial\,(Q_{P/N})}}{\dfrac{\sqrt{T_i}}{(1+x)\,C_1 A_t} - N\dfrac{\partial\, ft\left(\frac{\Delta P_p}{N^2}\right)}{\partial\left(\frac{Q_p}{N}\right)}}$$

$$\frac{\partial\tau_p}{\partial Q} = \frac{Q_p}{\eta_p}\,\frac{\partial\, ft\left(\frac{\Delta P_p}{N_2}\right)}{\partial\left(\frac{Q_p}{N}\right)} + \frac{\tau_p}{Q_p} - \frac{\tau_p}{N\,\eta_p} + \frac{\partial\,\eta_p}{\partial\left(\frac{Q_p}{N}\right)}$$

$$\frac{\partial\tau_p}{\partial_N} = \frac{Q_p}{\eta_p}\left[2\,ft\left(\frac{Q_p}{N}\right) - \frac{Q_p}{N}\,\frac{\partial\, ft\left(\frac{\Delta P_p}{N_2}\right)}{\partial\left(\frac{Q_p}{N}\right)}\right] - \frac{\tau_p}{N} + \frac{\tau_p}{\eta_p}\,\frac{Q_p}{N^2}\,\frac{\partial\,\eta_p}{\partial\left(\frac{Q_p}{N}\right)}$$

Table IV
Parameters in the Engine Linear Dynamic Model (Cont)

$$\frac{\partial \ \Delta P_T}{\partial X} = \frac{\partial \ ft \ (\frac{\Delta P_p}{N_2})}{\partial \ (\frac{Q_p}{N})} \ \frac{N \ Q_p \ \sqrt{T_i}}{(1 + x)\sqrt{T_i} - (1 + x)^2 \ C_1 \ A{+}N \ \dfrac{\partial \ ft \ \frac{(\Delta P_p)}{N^2}}{\partial \ \frac{(Q_p)}{N}}}$$

$$\frac{\partial \ \Delta P_T}{\partial N} = 2 \ N \ ft \ (\frac{Q_p}{N}) + \frac{\partial \ ft \ (\frac{\Delta P_p}{N^2})}{\partial \ (\frac{Q_p}{N})} \left[N \frac{\partial Q}{\partial N} - Q \right]$$

$$\frac{\partial \ \tau_T}{\partial \ \Delta P_p} = \frac{\tau_T}{\Delta P_p + P_T} + \left(\frac{2 \ \tau_T}{C_o} - \frac{Q_T \ \mu}{2N} \ \frac{\partial \ \eta_T}{\partial \ (\frac{\mu}{C_o})} \right) *$$

$$\left[\frac{C_2 \sqrt{T_i} \ P_c \ (\gamma - 1)}{2 \ \gamma \ (P_T + \Delta P_p)^2 \ (\frac{P_c}{P_T + \Delta P_p})^{\frac{1}{\gamma}} \ \sqrt{1 - (\frac{P_c}{P_T + \Delta P_p})^{\frac{\gamma-1}{\gamma}}}} \right]$$

$$\frac{\partial \ \tau_T}{\partial N} = \frac{\pi \ D_p}{720} \ \frac{\tau_T}{\eta_T \ C_o} \ \frac{\partial \ \eta_T}{\partial \ (\frac{\mu}{C_o})} - \frac{\tau_T}{N}$$

Refer to Table III for Definition of Symbols

C. SYSTEM PERFORMANCE

A basis of comparison is necessary in analyzing and designing control systems. Typical test signal inputs are step functions, ramp functions and acceleration or parabolic functions. By using a standard input which is representative of an actual input, a measure of system transient response can be made. For the OTV system the transient response of a unit step for thrust could be used to obtain the response time, percent overshoot and steady-state error. If the results of the analysis are unacceptable, for example the response time is too slow, the shaping filters and gains would be adjusted until satisfactory results are obtained. The response times of the preliminary model, at nominal thrust conditions (refer to Figures 10 and 11) are shown to be satisfactory. Simulations at many operating points need to be performed in order to verify the transient response over the throttling range. It is possible that a variable gain schedule may be required to achieve both adequate stability and response over this range.

D. CONTROL MODEL UPDATES

Future model updates that will add to the dynamic model fidelity include: 1) modeling of hydrogen regenerator , 2) a more accurate model of the combustion chamber heat transfer process, 3) additional line and cooling jacket capacitance equations, 4) the use of actual valve area characteristic curves as a function of stroke and valve actuator models and, (5) modeling of the LOX/GH_2 heat exchanger. It should be noted that the linearization process described previously only applies to single input - single output systems. In actuality the OTV system is a multiple input - multiple output system; i.e., thrust and mixture ratio; however, since the desired mixture ratio was assumed to be constant, the analysis is pertinent. A state-space representation is commonly employed for multi-variable feedback systems. This treatment provides analytic tools for determining the observability and controllability of the state variables, accounts for cross coupling effects, and can be used for determining optimum variable feedback gains over the range of operation. Software such as MATRIX-X, which is an integrated modeling, simulation, and control system package is available for this analysis. The control design module of MATRIX-X includes all linear system analysis functions including interactive classical and modern control design, conversion between model forms, and compu-

tation of time and frequency responses. Non-linear models can be created and simulated interactively. There are six different integration algorithms available for simulating continuous, hybrid (mixed continuous/discrete), and even multi-rate digital systems. A system identification module is also provided which enables the user to transform test data into accurate system models. It is available to facilitate modern controls analysis. One standard feature allows the user to transfer from the Laplace domain, used in classical controls, to the state-space representation of modern controls. The computing ability of this software will be very useful for future work if optimization or multiple feedback variable modeling become important design considerations.

E. CONTROL CONFIGURATION

The control configuration shown in Figure 7 is an approximation of the plant dynamics and feedback compensation for the system. A more detailed control logic is presented in Figure 13. In this concept the two basic feedback parameters are chamber pressure and oxidizer flow rate. The thrust and mixture ratio commands are rate-limited to avoid the possibility of severe system oscillations and thermal spikes or TPA stall. The commanded chamber pressure is calculated based on thrust and mixture ratio and fed forward to the feedback summing junctions and fuel and oxidizer turbine bypass valve schedules. Error signals between commanded chamber pressure and actual chamber pressure are fed through proportional plus integral controllers. These filtered signals are then summed with the table look-up stroke commands. At this point the total valve stroke signal actuates the valve to provide the desired compensation. The valve schedules are a multiple set of curves that give valve stroke as a function of engine chamber pressure and mixture ratio. Their basic function is to provide reasonable initial valve stroke positions so that controller modulation is kept to a minimum. Mixture ratio is controlled in the same manner as chamber pressure, with the difference that only the hydrogen turbine bypass valve is modulated for a steady position of the oxygen turbine bypass valve. The time base start and shutdown valve schedules for the fuel circuit are shown in Figures 14 and 15. Note that all the valves, with the exception of the turbine bypass valves, the regenerator bypass valves, the LOX/GH_2 heat exchanger valve and the fuel idle valve, are on-off valves. The on-off valve schedules are predetermined using dynamic simulation runs in order to achieve desirable start and shutdown characteristics. Included in the control logic is compensation for turbine inlet tem

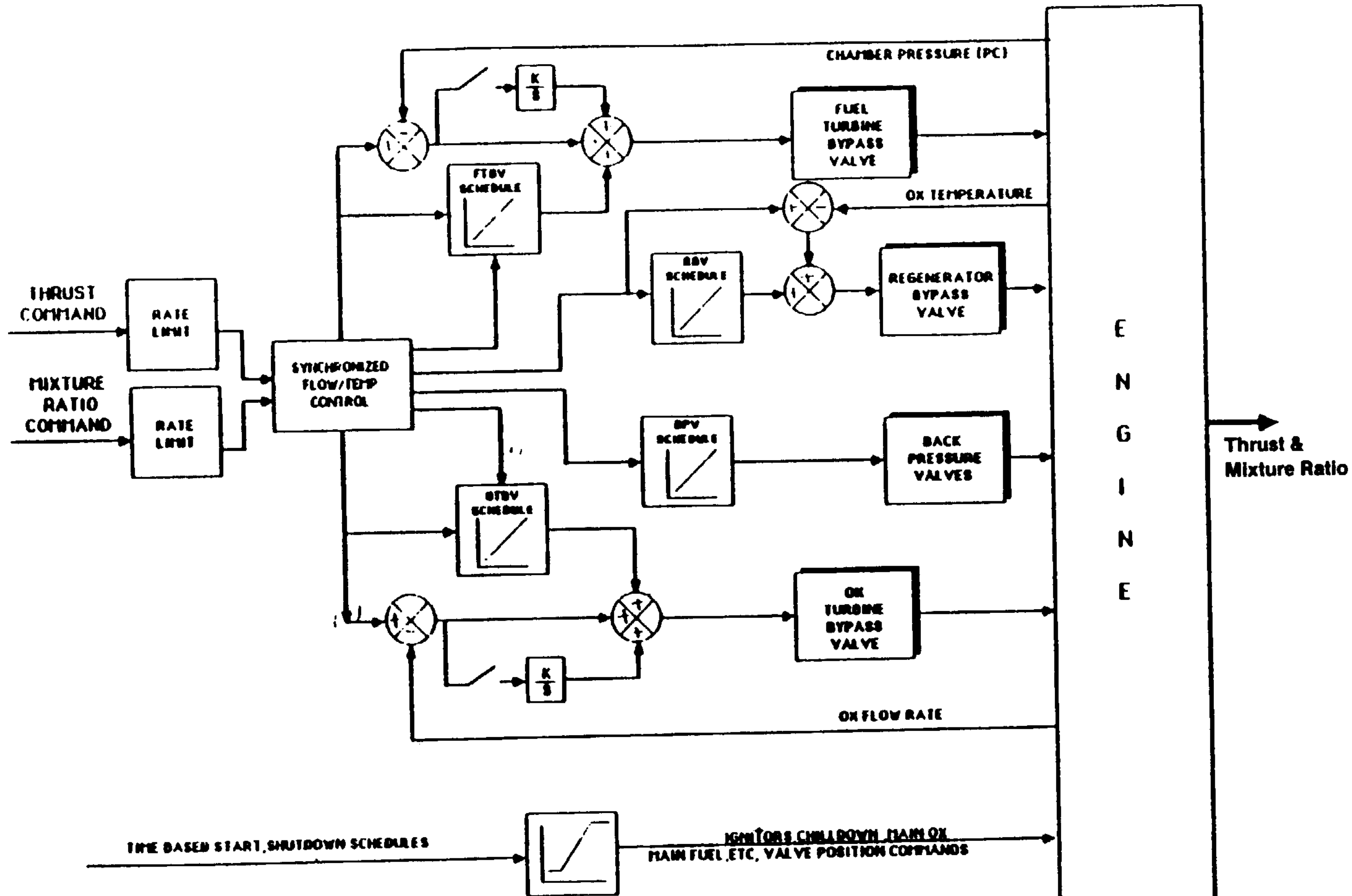


Figure 13. Selected Control Logic Provides Stable Engine Operation

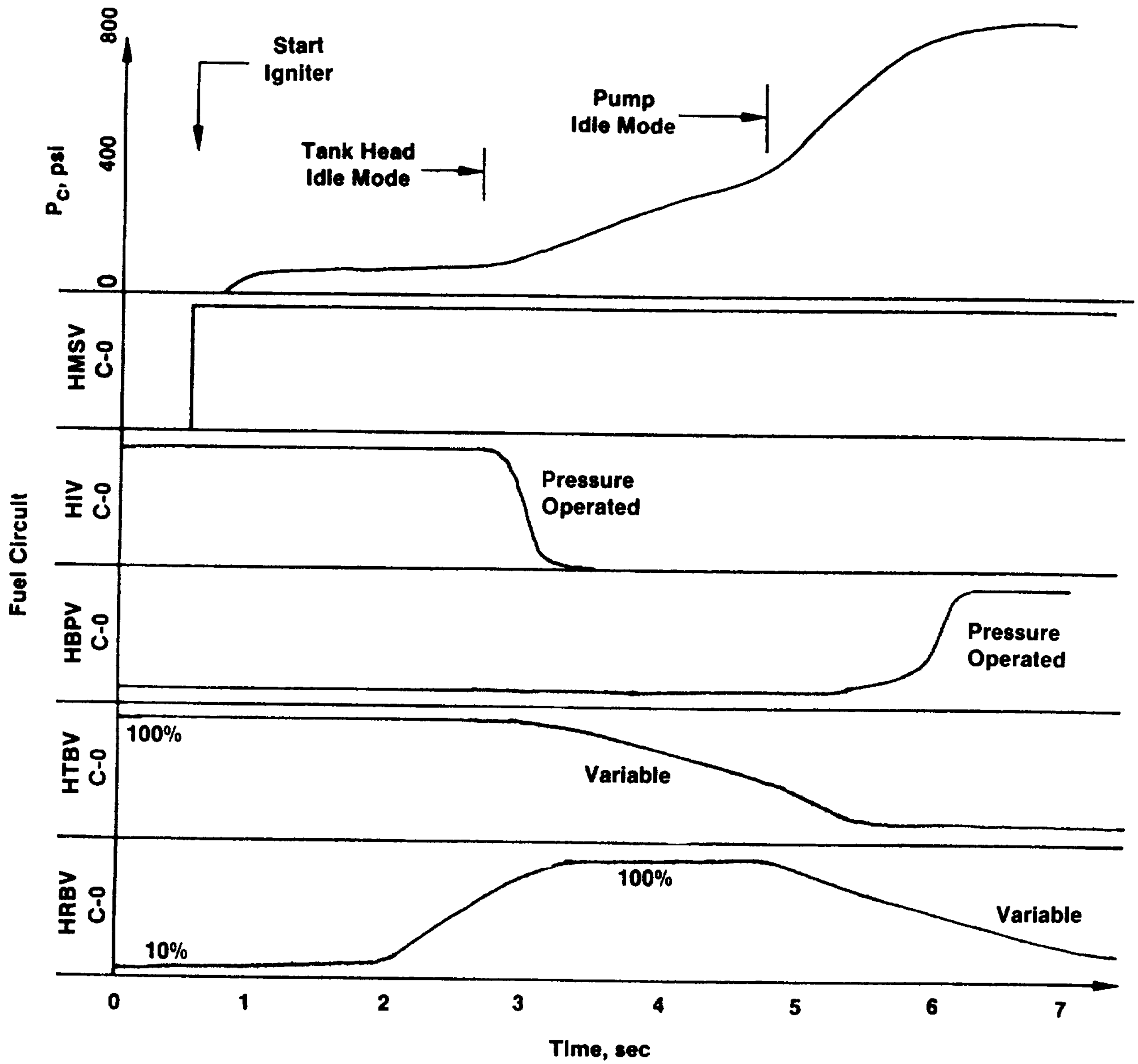


Figure 14. OTV Engine Start-up Sequence

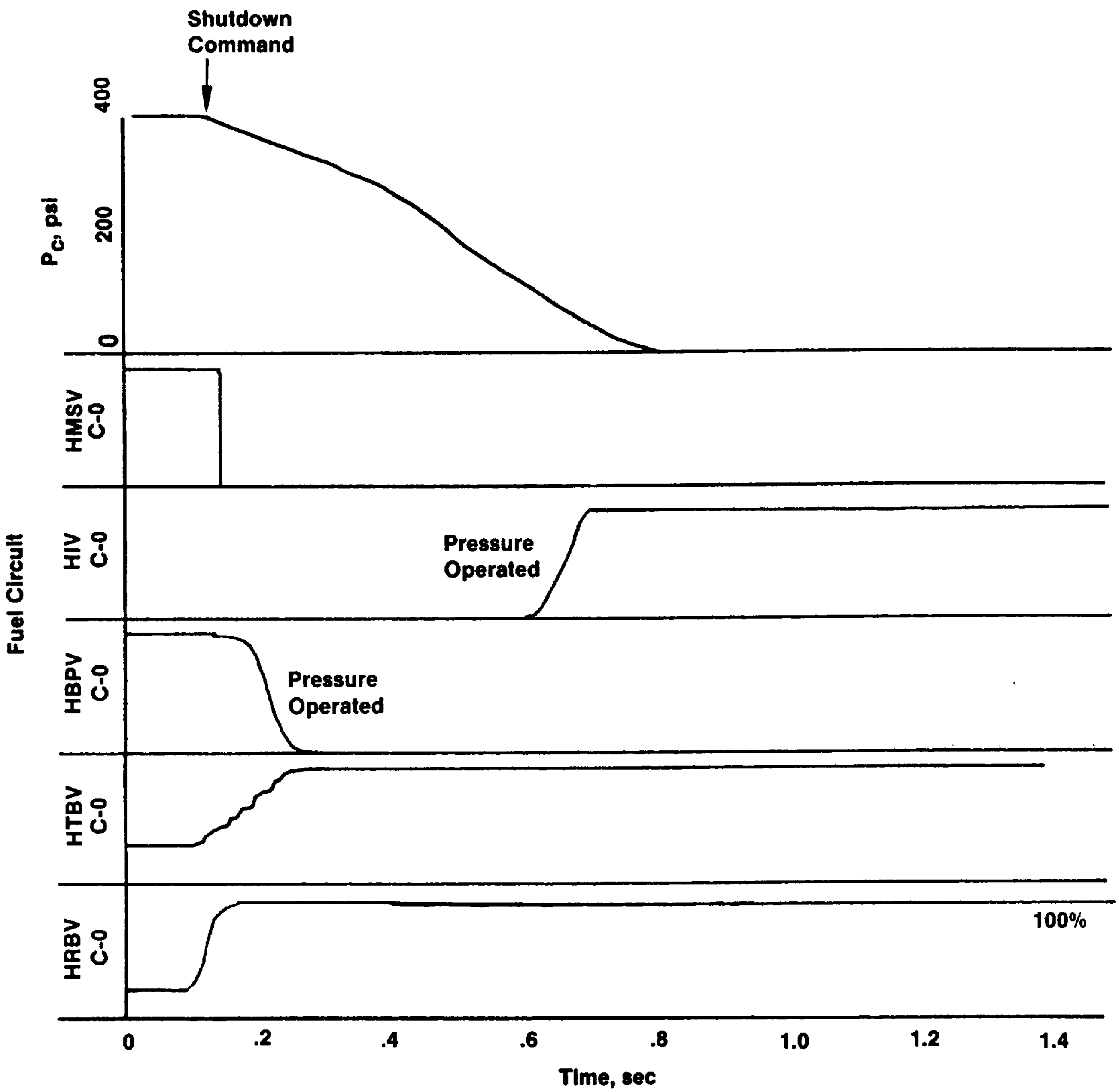


Figure 15. OTV Engine Shut-down

perature variations by use of regenerator bypass valves. The back pressure valves impose a high pressure drop during low chamber pressure engine operation so that the liquid oxygen converts to a high pressure gas under conditions well above the two phase dome. This is necessary to prevent two-phase flow into the injector.

V. CONTROL ELEMENT REQUIREMENTS

There are four basic control elements: 1) the various flow control valves, 2) those sensors specifically identified for engine controller use, 3) the controller hardware, and 4) the control software/firmware. In addition, supplementary information can be gained from health management sensor data if suitably processed. For a piloted version of the OTV, commands from the pilot's station can direct controller operation. An unmanned OTV would have vehicle guidance computer and telemetry inputs that would direct controller (and engine) operation.

A. CONTROL VALVE REQUIREMENTS

The basic control valve configuration is illustrated in Figure 4b. Of the 12 valves depicted, five are modulation valves and seven are on-off valves. Table V is a list of of the individual valve functions. The valve operating environments are based on engine operating range extremes. Single page specifications for each valve are given in Appendix B.

B. CONTROL SENSOR REQUIREMENTS

Table VI gives a listing of the specified engine sensors, their purpose, operating ranges and types. Appendix B includes a complete listing of sensors with a summary of the ranges and operating characteristics. The sensors given in Table VI are necessary elements of the control system and serve as a logical starting point for developing sensor requirements for health management applications.

C. ENGINE CONTROLLER REQUIREMENTS

ATC has baselined the use of a controller developed under an IR&D program. This engine controller may be readily adapted to handle all of the OTV engine control requirements. Important features of the IR&D controller are: the use of hybrid microelectronics which are inherently small, light and rugged; dual channel redundancy architecture to eliminate single point failures; low power requirements; small size and low weight. The controller requirements of the OTV engine, which were compiled on the basis of the selected control logic, sensors and valves, is given in Table VII. The corresponding IR&D interface data are found in Table VIII. By comparing the information given in Tables VII and VIII, it is appar-

TABLE V
OTV ENGINE CONTROL VALVES

VALVE NAME	ABBREVIATION	FUNCTION	FLUID	OPERATING ENVIRONMENT	TYPE
Oxygen Main Shutoff	OMSV	Propellant Isolation	Liquid O_2	0 to 45 psia -310 to -298°F	PO were Open/ Solenoid Latch/ Spring Loaded Closed
Hydrogen Main Shutoff	HMSV	Propellant Isolation	Liquid H_2	0 to 45 psia 0 to 40°R	Powered Open/ Solenoid Latch/ Spring Loaded Closed
Oxygen Turbine Bypass	OTBV	Mixture Ratio Control	Hot GOX	0 to 5000 psia 0 to 500°F	Servo/Pintle Fails in Place
Hydrogen Turbine Bypass	HTBV	Thrust Control	Hot GH_2	0 to 6000 psia 0 to 1000°F	Servo/Pintle Fails in Place
Hydrogen Regenerator Bypass Valve	HRBV	Fuel Circuit Temperature Control	Cold GH_2	0 to 5600 psia -340 to -420°F	Modulating Poppet Fails in Place
Heat Exchanger Bypass Valve	HEBV	Oxygen Circuit Temperature Control	Hot GH_2	0 to 2700 psia 0 to 800°F	Modulating Poppet, Fails in Place
Hydrogen Idle Valve**	HIV	Idle Operation MR Control	GH_2	80 psid, 0 to 6000 psia -360 to 540°F	Modulating poppet, fails closed**
Oxygen Back Pressure	OBPV	Heat Exchanger Pressure Control	Warm GO_2	200 psid, 0 to 5000 psia -250 to 400°F	Open/Partial* Closure
Hydrogen Back Pressure	HBPV	Pressure Balance During Start	Warm GH_2	200 psid, 0 to 6000 psia -360 to 600°F	Open/Partial* Closure

TABLE V (cont.)

OTV ENGINE CONTROL VALVES

VALVE NAME	ABBREVIATION	FUNCTION	OPERATING FLUID	ENVIRONMENT	TYPE
Igniter Flow Control(2)***	OICV, HICV	Igniter Propellant Flow Control	GH_2, GO_2	0 to 6000 psia -400 to 100°F	Powered/Open Spring Loaded Closed
Oxygen Tank Pressurization	OTPV	Oxygen Tank Pressurization Control	Warm GO_2	0 to 3000 psia 0 to 400°F	Powered Open/ Spring Loaded Closed
Hydrogen Tank Pressurization	HTPV	Hydrogen Tank Pressurization Control	Warm GH_2	0 to 5000 psia 0 to 800°F	Powered Open/ Spring Loaded Closed

* Pressure operated. No electrical actuation devices. These valves are used to raise circuit pressure high enough to avoid the two-phase dome for the oxygen heating and the consequent film boiling in the heat exchanger.

** A pressure operated valve is an option.

*** Not shown on engine schematic.

As of April 1988.

Table VI
Engine Sensors for Baseline Control Logic

		MEASUREMENT	PURPOSE	OP. RANGE	TYPE	FLUID
PRESSURE	1	CHAMBER	THRUST CONTROL	0 TO 3500 PSIA	STRAIN GAGE (TEMP. COMP.)	HOT GO2+GH2
	2	OX. PUMP DISCHARGE	OX. DENSITY CALC.	0 TO 4500 PSIA	STRAIN GAGE (TEMP. COMP.)	LO2
	3	FUEL PUMP DISCHARGE	FUEL DENSITY CALC.	0 TO 4500 PSIA	STRAIN GAGE (TEMP. COMP.)	LH2
TEMPERATURE	1	OX. PUMP DISCHARGE	OX. DENSITY CALC.	-310 TO -260 F	RESISTANCE TEMPERATURE DETECTOR (RTD)	LO2
	2	FUEL PUMP DISCHARGE	FUEL DENSITY CALC.	-423 TO -340 F	RESISTANCE TEMPERATURE DETECTOR (RTD)	LH2
	3	OX. TURB. INLET	TEMP. LIMIT CONTROL	0 TO 500 F	RESISTANCE TEMPERATURE DETECTOR (RTD)	HOT GO2
	4	FUEL TURB. INLET	TEMP. LIMIT CONTROL	50 TO 300 F	RESISTANCE TEMPERATURE DETECTOR (RTD)	HOT GH2
FLOW RATE	1	OX. PUMP DISCHARGE	OX. WDOT CALC.	0 TO 0.25 CFS	ULTRASONIC FLOWMETER	LO2
	2	FUEL PUMP DISCHARGE	FUEL WDOT CALC.	0 TO 0.60 CFS	ULTRASONIC FLOWMETER	LH2
VALVE POS'N	1	OX. TURBINE BYPASS VALVE	SERVO VALVE CONTROL	TBD IN	LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (LVDT)	TBD
	2	FUEL TURBINE BYPASS VALVE	SERVO VALVE CONTROL	TBD IN	LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (LVDT)	TBD
	3	OX. IDLE VALVE	SERVO VALVE CONTROL	TBD IN	LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (LVDT)	TBD

Table VII

Selected Control Logic, Sensors and Valves Drive the Controller Requirements

Vehicle to Controller Interfaces:	
Avionics Power Bus	1
Utility Power Bus	1*
Serial Command Channels	1*
Power-up Command Channels	1
Discrete Status Channels	1*
Controller-to-Engine Electrical Interface:	
On/Off Valves	7
Throttling Valves (Analog Commands)	3
Pressure Sensors	3
Temperature Sensors	4
Speed** Sensors or Vortex Shedding Flowmeters	2
Valve Position (Analog Inputs)	3
Regulated Avionics	1
Ground Support Equipment Interface:	
Serial I/O	1
Discrete Inputs	1
Analog Outputs (Test Points)	4

*Optional

**At Low Speeds both TPA Speed and Flowmeter Readings must be used to Assure Adequate Mixture Ratio Control.

Note: Quantities Listed are Per Channel

TABLE VIII

IR&D ENGINE CONTROLLER - ENGINE INTERFACES

Function	Quantity
Solenoid Valves/Devices	12
Pressure Sensors	8
Temperature Sensors - TC	2
Temperatures Sensors - RTD	2
Turbine Speed Sensors	2
Valve Position Sensors	1
Analog Commands	2
Discrete Commands	8
Analog Inputs	12
Vortex Shedding Flowmeters (2 in series)	4

(Quantities Listed On a Per Channel Basis)

TABLE VIII (cont.)

IR&D ENGINE CONTROLLER - VEHICLE INTERFACES

Function	Quantity
28 VDC Avionics Power	1
28 VDC Utility Power	1
Power-Up Command	1
Discrete Command Channels	3
Serial Command Channels	1
Serial Data Channels	1

(Quantities Listed On A Per Channel Basis)

ent that the IR&D controller could be used on the OTV engine with minimal modifications.

The IR&D controller has a 128K word memory capacity; approximately 34K of this memory is required for engine control. Because the IR&D controller has a generous amount of surplus memory space, its application to the OTV program should not impose any limitations to control capabilities.

Additional considerations dictated by multi-engine control remain to be examined. For example, start transient coordination, engine-out coordination compensation and gimballing are issues that will effect the final engine controller requirements for a multi-engine system.

VI. HEALTH MANAGEMENT

A. HEALTH MANAGEMENT SYSTEM DESCRIPTION

The rationale for a health management system is to eliminate the high cost of losing a mission because of engine failure, and to reduce the high cost of returning space based engines to earth for servicing. It is a collection of methods for improving engine system reliability, performance and cost effectiveness through early fault detection and preventive maintenance. Functions provided by the health management system include: pre-flight engine check-out, detection of out-of-limit conditions, fail-operational/fail-safe fault tolerance for all flight critical functions, recognition of sudden shifts in performance, trend data collection and storage, off-line extrapolation of performance trends to plan scheduled maintenance, and modular fault isolation to permit more cost effective maintenance. The health management system functions continuously during engine operation and during pre- and post-checkout. At pre-flight testing it will evaluate the health of the engine sensors. After the flight it will process collected data and signal commands for required maintenance. The health management system will sequentially collect signals from sensors, process the signal data for efficient use, diagnose the engine component behaviors and evaluate actual engine system performance against commanded performance during the flight mode. Figure 16 illustrates the health management system flow paths.

B. ENGINE FAILURE MODES

A compilation of internal and component OTV engine failure modes is presented in Table IX. The health management system is responsible for detecting anomalies during engine operation caused by any of these failure modes either by direct sensor measurement or computational algorithms. The hierarchical structure of the health management system is shown in Figure 17. The red-line sensors are of primary importance for engine prognosis. If the red-line limits are exceeded during engine operation, shut-down commands are issued to the controller processor in order to avoid a catastrophic failure. Many of the red-line parameters are not measurable quantities; however, state estimation algorithms can be used to ascertain the unknown values from the measured data. The pink-line sensors are at a lower level in the health management architecture. The information provided by these sensors is compared with the established pink-line limits. Engine operation

Software Level	Task	Interface	Hardware Level
Controller	Operation Commands Engine Control Restructure Mission Profile Evaluation Maintenance Scheduling Multi-Engine Interaction	On Line Real Time	Engine System Controller Operator Inputs
Prognosis	Model Restructure State Estimation Parameter Identification Parameter Trend Analysis Component Evaluation Failure Mode Detection		Engine(s) Component
Diagnostic	Data Acquisition Signal Processing Faulty Signal Detection Data Reconstruction Signal Preconditioning Sensor Recovery Evaluation	On Line Real Time	Sensor/Actuator, Controller
Report & Record	Operator Display Telemetry Data Selection Health History Recording Health Prognosis Display	Real Time Real Time Selective Delay Real Time Readout on Command	Vehicle

Arrows indicate the direction of data flow or commands. For instance, vehicle operator (pilots or a control center remotely located but in radio contact with the vehicle) can make inputs through an interface to the engine controller. The HM system also channels information to the operator display as either real time data, selective data, analyzed data with a time delay, or data commanded by the operator.

Figure 16. Health Management System Configuration

TABLE IX

OTV ENGINE FAILURE MODES

Component	Failure Modes
TPA	Pressure Loss in Hydrostatic Bearing
	Turbine Blade Chipping or Cracking
	Oxygen Turbine Fire due to Rubbing
	Nozzle Erosion Crack
	Corrosion or Fatigue Failure
	Pump Cavitation Damage
	Seal Rupture
TCA	Blanching
	Cooling Channel Contamination
	Injector Contamination
	Chamber Fatigue Cracking
	Connection Leak
	Overheating/Undercoolng
Line	Connection Leak
	Line Cracks
Valves	Open Circuit (Electrical)
	Sensor Malfunction (No Position Indictation)
	Electrical Short
Engine Sensor	Malfunction (Change in Bias, Failure)
	Interface Break-Down
Igniter	Igniter Valve Failure
	Spark Plug Failure
Controller	Open Circuit/Short
	Module Break-Down
	Interface Break-Down
	Cooling System Failure
	Algorithm Defect

- EACH LAYER OPTIMIZED FOR ITS OWN FUNCTION
- CONTROL ISOLATED FROM HEALTH MANAGMENT FAILURE
- MODULAR STRUCTURE AIDS DEVELOPMENT

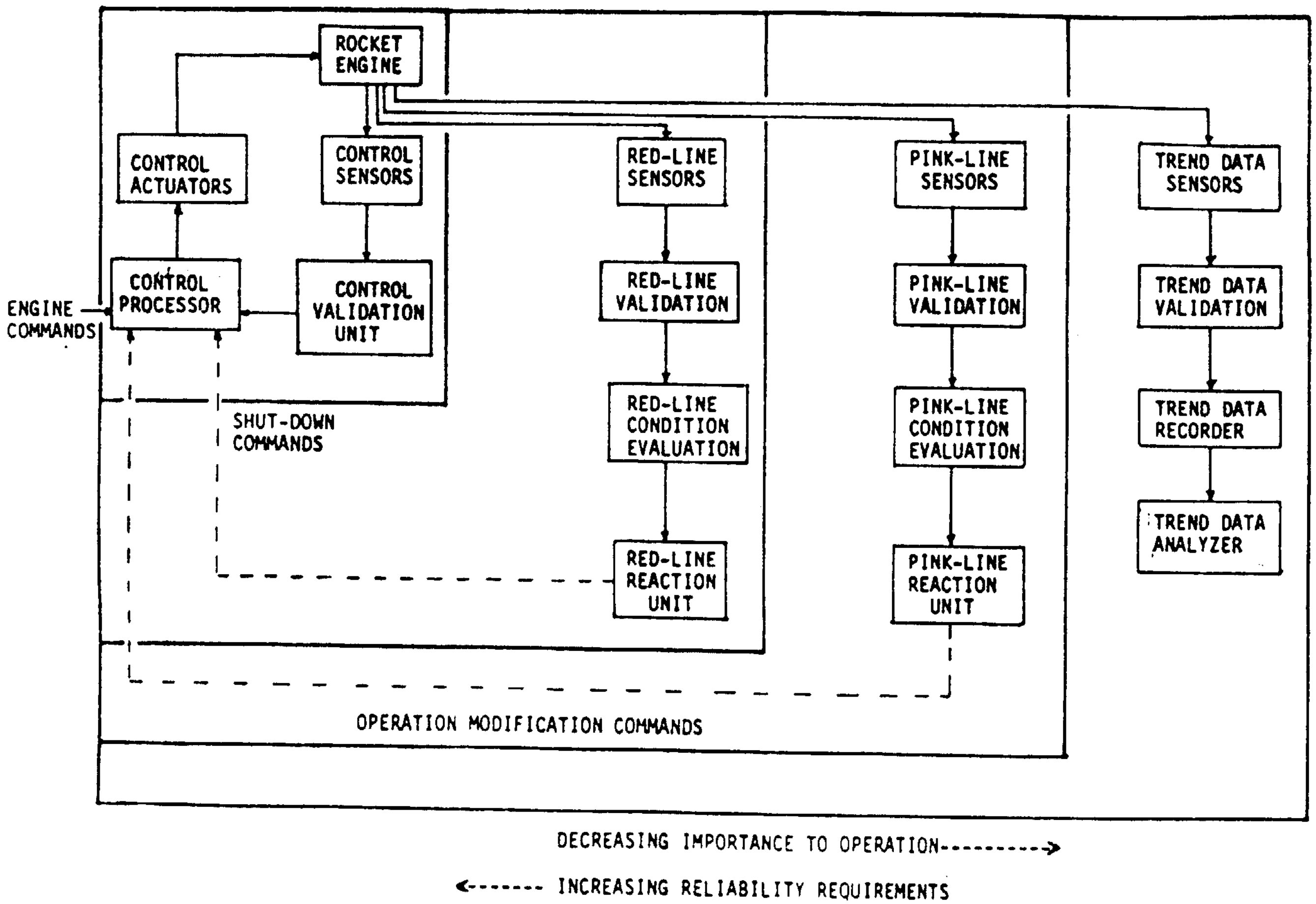


Figure 17. Layered HM/C System Architecture

modification commands are sent to the control processor if any of the pink-line limits are exceeded. Prompt preventive measures during engine operation are needed to avoid more serious consequences. The generalized detection algorithm flow diagram is depicted in Figure 18.

Component or engine failures can be due to external causes as well as faults within the engine system. The space environment includes high radiation levels that can destroy electronic parts and weaken structural materials. A comprehensive health management system should include radiation dose recorders with an alerting system when critical levels are approached. Also there is an ever present hazard from micrometeorites and space debris that could be responsible for a variety of failures. The health management and control system must be able to effect a timely engine shutdown after such an encounter. The aerobraking maneuver also poses some hazards. Failure of an engine cover door would place the engine system in a high temperature, highly fluctuating aerodynamic load environment. The likely failure would be in the extendible exit cone, but high temperatures could destroy control elements. The health monitor system would have to assess damage prior to any engine start attempt. The multiple possibilities for electrical failure require mechanical backup such as valves that are spring loaded closed on power failure. These are the most obvious externally caused failures, but there are others. The health management system should be designed to safely handle all of them.

C. DESIGNING FOR SYSTEM RELIABILITY

Any complex data system must be designed to accommodate normal operating fluctuations and measurement error. Since noise and general system disturbances are random processes, statistical methods are used to filter all measured data. The reliability of the digital electronic control system can be improved by incorporating control component redundancy at the sensors, the actuators, or the controls computer itself.

The two types of sensor redundancy techniques use hardware and/or analytical programs. Analytical redundancy uses a reference model of the engine to provide redundant estimates of a measured engine variable using a data base from high reliability sensors. Hardware redundancy uses multiple sensors to measure the

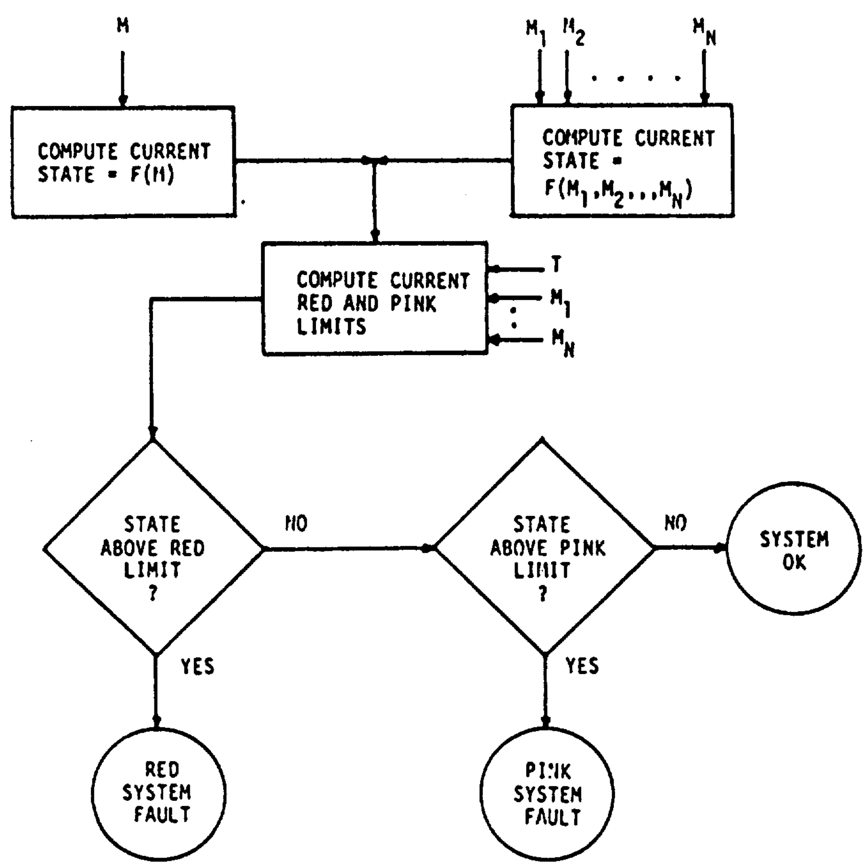


Figure 18. Generalized Detection Algorithm Flow Diagram

same variable. Voting strategies can then be used to detect and isolate sensor failures so that a faulty sensor can be eliminated from the system without initiating a false command. A disadvantage of hardware redundancy is that it is insensitive to the type of failure, hard or soft, since any discrepancy between two redundant sensors always signals a failure. Hard failures are classified as failures that are out-of-range or large-in-range failures, soft failures are small in-range or small bias shifts. Other drawbacks to hardware redundancy are reflected in added component complexity, cost, and weight. Analytical redundancy is able to distinguish hard and soft sensor failures. Range or rate checks are used to provide successful detection of hard sensor failures and statistical decision theory and optimal filtering are used to detect soft failures. A functional block diagram of a sensor fault algorithm is shown in Figure 19. A sample of a detection algorithm is given in Figure 20. State estimate techniques are commonly used for analytic redundancy; however, limitations are imposed by the necessity of an accurate linear model and the assumption that the disturbances on the system are well modeled or else have an insignificant effect on plant or parameter variations. A new approach that eliminates the need for state-space computations uses the estimation error space of each observer in a bank of observers to detect and isolate sensor failures.

A very important benefit of a multiple engine system configuration is the improvement in the redundancy capabilities of the health management system. For example, sensor measurement data from one engine can be used as redundant information for sensor failure detection on another engine. Since proper control response requires comparison of key operating variables from each engine, the interconnection of systems is already necessary, and the benefit to health management is obtained at little extra cost.

In an earlier task a Failure Modes and Effects Analysis (FMEA) was completed for the OTV engine. This analysis was updated and is included as Appendix C as it is still relevant to the baseline engine design. The analysis covers the critical components. Other failures are possible. The list of failure modes in Table IX was generated using the FMEA.

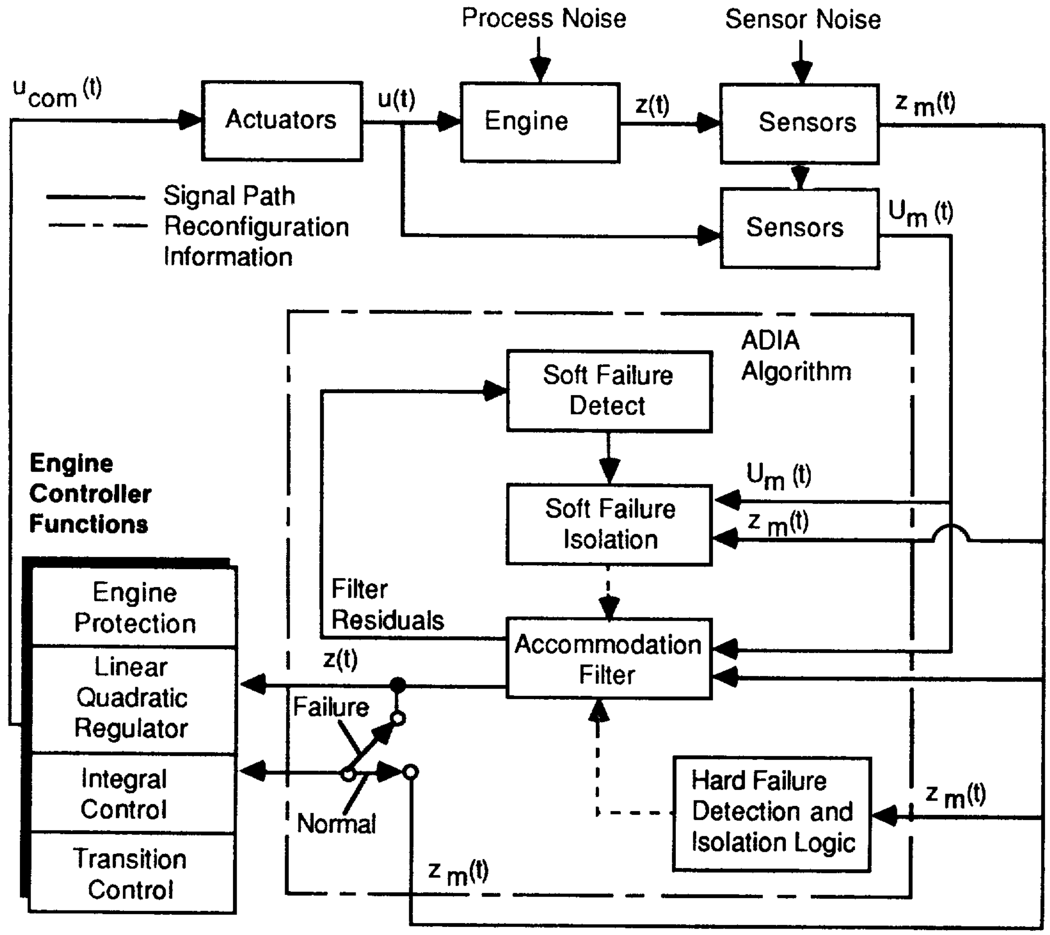


Figure 19. Testbed System with Advanced Diagnosis Algorithm (ADIA)

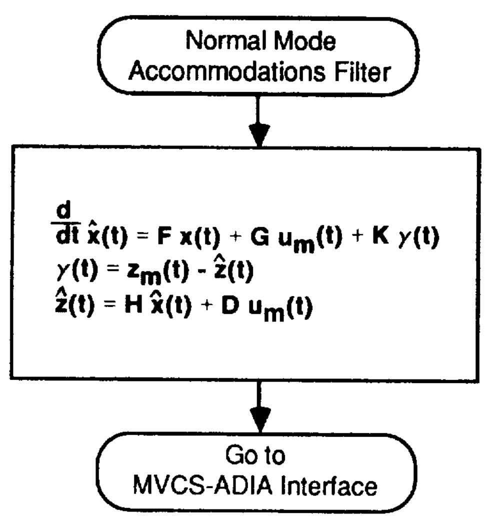


Figure 20. Normal Mode Accomodation Filter Logic

D. MODULAR HEALTH MANAGEMENT SYSTEM DESIGN

The health management algorithms have been classified under three levels of implementation: engine, component and sensor. The general structure is outlined in Table X according to the task performed, algorithm used and available software to perform the task. The functional descriptions of these algorithms at the engine sensor levels is detailed in Tables XI and XII, respectively. Some of the health management task objectives may be limited by the sensor and computational capabilities of the system.

The component failure detection algorithms compare actual to expected component performance. Expected performance is derived from analytical component models, developmental hardware testing, and prior component experience. System measurements are used to determine actual performance. A disparity between actual versus predicted performance signals the health management system to take appropriate corrective actions. An example of fault detection/verification logic for a gas generator-driven TPA is shown in Figure 21.

A block diagram of the basic flow paths of the health management module is shown in Figure 22. The system is subdivided into a set of real-time and off-time functions. Real-time functions which occur during engine operation include: sensor measurement validation, sensor and component failure detection, isolation and accommodation, data acquisition and alarm signaling. Off-time functions are performed during pre- and -post-flight regimes for assessment of engine readiness and maintenance needs.

E. HEALTH MANAGEMENT DATA STORAGE

A number of possibilities exist for data storage of health management data. Available memory technologies and their associated attributes are summarized in Table XIII.

The health management data recorder requirements differ somewhat from those for the engine controller. More memory storage is necessary; however, the processing requirements for health management data recording are less than

Table X
Health Management Algorithm

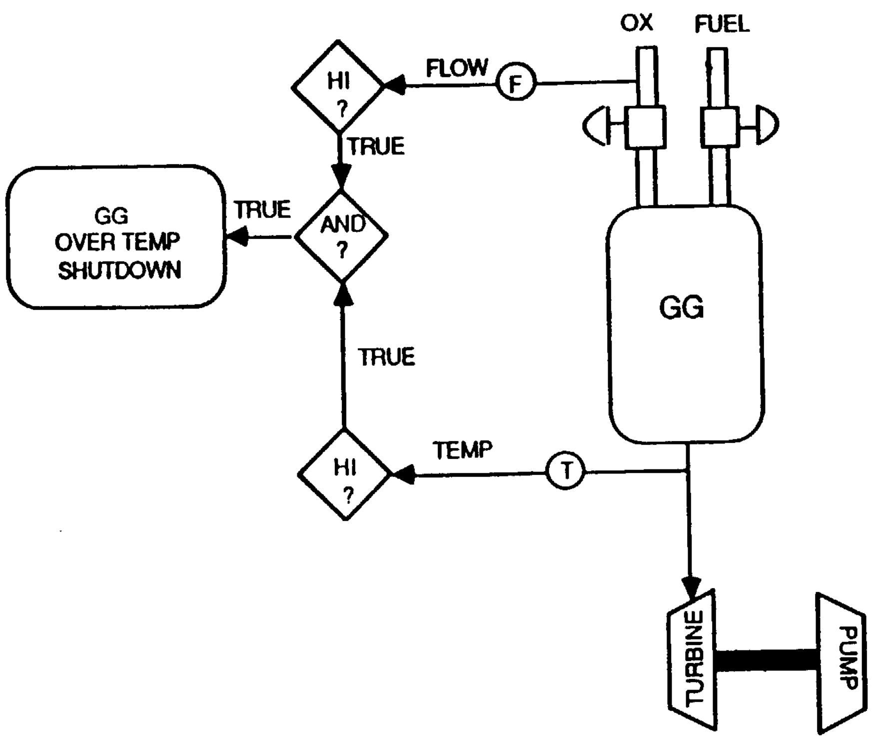
Level	Task	Algorithm	Software Type	Software Code
Sensor	Data Acquisition	Protocol		Assembly
	Signal Conditioning	Filter	Band Pass Filter	Jovial/Ada
	(Preconditioning)	Compensation	(Simple)	Jovial/Ada
	Failure Detection	Redundancy Management		Jovial/Ada
(Component)		Level Checking	(Simple)	Jovial/Ada
(Component)		Signature Analysis	Time Series, FFT	Jovial/Ada
	(Data Construction)	Kalman Filter	Kalman Filter	Jovial/Ada
	Sensor Evaluation	Diagnostic Testing/Calibrating/ Requalifying		Lisp/ Expert
Component	Model Construction	Status Diagnostic		Lisp/ Expert
	State Estimation	Kalman Filter	Kalman Filter	Jovial/Ada
	Parameter Ident.	Recursive Least Squares	Optimization	Jovial/Ada
	Trend Analysis	Regression Modeling	Time Series	Jovial/Ada
	System Ident.	Verify Component	FFT	Jovial/Ada
	Failure Detection	Failure Diagnostic		Lisp/ Expert
		Condition Prognostic		Lisp/ Expert
Engine	Report/Document	Data Base Management		Lisp/ Expert
	Engine Reconfig.	Failure Mode Management		Lisp/ Expert
	Mission Evaluation	Mission Profile Analysis		Jovial/Ada
	Maintenance Schedule	Logistic Management		Lisp/ Expert
	Engine Command	Command Schedule		Jovial/Ada

Table XI
Health Management Software at Engine Level

Task	Algorithm	Function Description
Model Construction	Status Diagnostic	Failure Mode Compensation
State Estimation	Kalman Filtering	Estimate State
Parameter Identification	Recursive Least Squares	Identify System Parameter
Parameter Trend Analysis	Regression Modeling	Predict Engine Condition
Component Evaluation	System Identification	Verify Comp. Character
	Level Checking	Level, Rate Threshold
	Signature Analysis	Pattern Recognition of Component
Failure Mode Detection	Failure Diagnostic	Identify Failure Mode
	Condition Prognostic	Identify Health Condition
Report/Document	Data Base Management	Manage Health Monitoring Data
Engine Reconfig.	Failure Mode Management	Reconstruct Engine Geometry
Mission Evaluation	Mission Profile Analysis	Evaluate Mission Profile
Maintenance Scheduling	Logistic Management	Post Flight Maintenance Schedule
Engine Command	Command Schedule	Engine Reconfig. Compensation
Signal Routing	Protocol	Supply User Functions: 1) Controller 2) Vehicle Operator 3) Telemetry 4) Health Monitor Recorder

Table XII
Health Management Software at Sensor Level

Task	Algorithm	Function Description
Data Acquisition	Protocol	Multiplexing
		Sensor Status Registration
		Sampling Rate
		Data Storage
Signal Conditioning	Filter	Noise Separation
	Compensation	Gain Tuning
Failure Detection	Redundancy Management	Voting, Averaging, Mid-Value
	Level Checking	Level, Rate Threshold
	Signature Analysis	Pattern Recognition, Self Inspection
	Kalman Filtering	State Estimation
Data Construction	Kalman Filtering	Estimate State
Signal Preconditioning	Filter	Disturbance Isolation
Recovery Evaluation	Diagnostic Testing	Testing Sensor
	Calibration	Calibrating Sensor
	Requalification	Requalifying Sensor
Signal Routing	Protocol	Supply User Functions: 1) Controller 2) Vehicle Operator 3) Telemetry 4) Health Monitor Recorder



Note: Example Only; Not an OTV Engine System

LOGIC TABLE

GG EXIT TEMP	FLOW	CONDITION
OK	OK	GG OK
HI	OK	GG TEMP FAILURE OR OTHER PROBLEM
OK	HI	FLOW FAILURE OR OTHER PROBLEM
HI	HI	GG OVERTEMP

Figure 21. Example of a System Fault Detection/Verification Logic for a Gas Generator Turbine Drive System

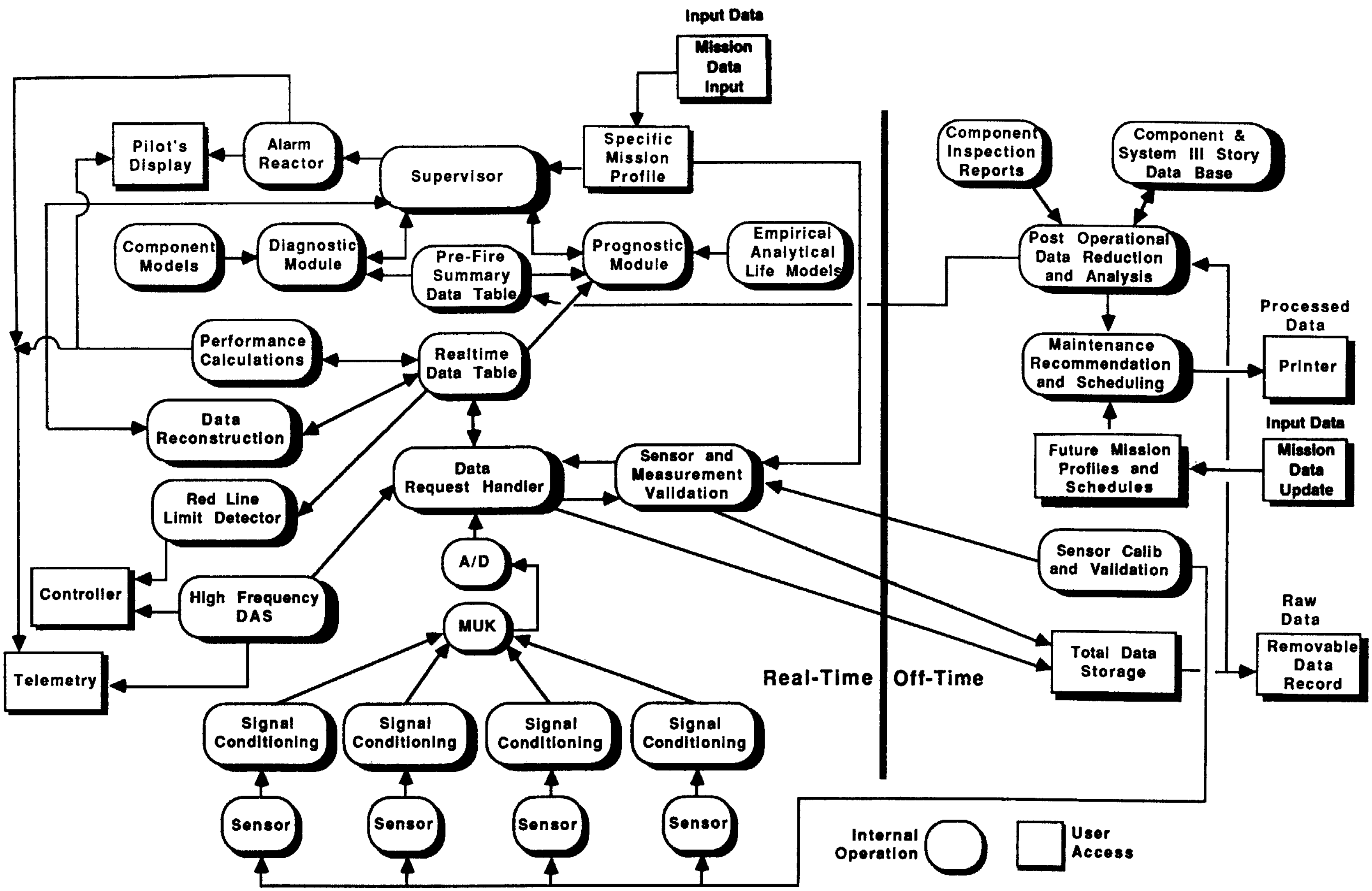


Figure 22. Condition Monitoring Block Diagram

TABLE XIII

AVAILABLE DATA STORAGE TECHNOLOGIES

1. SOLID STATE MEMORY
   - Fastest approach possible
   - Requires more volume for storage than other technologies
   - Very rugged and easy to interface

2. MAGNETIC MEMORY DEVICES
   - Magnetic Tape Drives - Extensive use for aircraft and unmanned satellites
   - Bubble Memory Devices - Rugged but low density and power hungry
   - Ruggedized Hard Discs - High storage capacity and speed

3. OPTICAL DISKS - DERIVED FORM CONVENTIONAL COMPACT DISK TECHNOLOGY
   - Write once read only memory (WORM)
   - Gaining acceptance for use in military aircraft
   - Very high data capacity (1/2 gigabyte per 5" disk)

TRADES REQUIRED TO MAKE DECISION
- Total data traces to be recorded
- Sample rates of the data traces
- Susceptibility to radiation environment

that for the real-time control computations of the controller. Single-string electronics are sufficient for non-flight critical functions and there are essentially no output electronics required for the data recorder.

Selected data streams will be processed and used for pilot display. At a minimum there will be a real time presentation of the following information for each engine:

1. Position in the start or shutdown sequence
2. Engine thrust
3. Engine mixture ratio
4. Turbine inlet temperatures (O_2 and H_2)
5. Gimbal position
6. Engine compartment temperature
7. Extendible exit cone position
8. Fuel and Ox start valve position
9. Turbine speed (O_2 and H_2)

Operation of a piloted space vehicle will be closely monitored by the spaceport and earth-based stations. Engine condition will be part of the routine telemetry broadcast from the OTV. The telemetry will include normal operational data but will be expanded to add data on red line or emergency conditions encountered during a mission. This is real-time data and may differ from the recorded data and pilot display information.

F. APPLICATIONS FOR ARTIFICIAL INTELLIGENCE AND EXPERT SYSTEMS

A comprehensive health management system will produce an enormous amount of data. At any given time most of it is redundant or irrelevant. Discrimination between pertinent and useless data requires informed judgement. Traditionally this is where a human takes over from the machine, but any person or even a whole crew will be unable to handle the mass of data for real time decision making. Data selection will have to be a function of the computer with only limited crew-directed additions. The computer should be capable of bringing a potential problem to the crew's attention, suggesting solutions, evaluating pilot input commands, and presenting alternatives should the pilot input be predicted to worsen

the problem. When time does not permit dialog with a human the computer must act to save the mission and/or the vehicle while informing the crew of the problem and the corrective action taken. These capabilities are at the current state-of-the-art, and will have to be developed for future manned space travel. The use of expert systems software will be needed for these demanding applications.

G. HEALTH MANAGEMENT SENSORS

The group of sensors required for basic engine control was described previously and is shown in Table I. Additional sensors are used to supplement the control sensors for the purpose of health management. Specifically, they are used for failure detection, isolation and accommodation, performance monitoring, and data acquisition of non-critical flight parameters used for post-flight maintenance analysis. A combined list of control and health management sensors is presented in Table XIV. A more detailed listing is given in Appendix B.

A review of advanced technology was made for bearing monitoring, pressure measurement, shaft monitoring, and hot spot detection. Bearings are critical life-limiting components in rocket engine turbopumps, thus bearing monitoring is an important facet of the health management system. The function of shaft monitors is to measure axial and radial shaft deflection and shaft speed all of which may be used for TPA diagnostics. Preliminary requirements for a displacement sensor are given in Table XV.

Currently silicon microchip displacement sensors are one of the more effective means of measuring rolling contact bearing outer race deflection. This measurement gives a direct indication of bearing health. Race deflection is sinusoidal in nature due to the balls passing by the sensing element as they travel around the race, refer to Figure 23. The signatures created by the balls are analyzed to determine bearing defects. By comparing the signatures of a good bearing with a bearing containing a defective ball, Figure 24, it is evident that this method provides a straightforward means of fault detection.

The objectives of investigating advanced sensor technologies for shaft monitoring are: to provide significant size and/or weight reduction, reliable operation at cryogenic temperatures, and improved packaging of signal conditioning

TABLE XIV

CONTROL AND HEALTH MANAGEMENT SENSORS

Component	Required Measurements	Function
Pump	Flow Rate Shaft Speed Inlet Pressure Discharge Pressure	Head, Flow, Speed Relationships and Cavitation Effects
Turbine	Shaft Speed Inlet Pressure and Temperature Outlet Pressure and Temperature Shaft Vibration Turbine Blade Temperature Turbine Blade Clearance	Turbine Performance Verification Turbine Blade Health
Bearing	Bearing Supply Pressure Bearing Temperatures Hydrostatic Channel Flow Rates Radial Shaft Motion Transducers Axial Shaft Motion Transducers Shaft Speed	Bearing Health, Efficiency
Thrust Chamber	Coolant Jacket Inlet and Outlet Pressures Coolant Jacket Inlet and Outlet Temperatures Chamber Pressure External Coolant Jacket Wall Temperatures for Hot-Spot Detection	Thrust Chamber Health and Performance

TABLE XIV (cont.)

Component	Required Measurements	Function
Control Valves	Valve Upstream and Downstream Pressures Valve Position Acoustic Internal Leak Detectors "Sniffer-Type" External Leak Detectors	Valve Monitoring
Injector	Injector Inlet Pressure Chamber Pressure Injector Inlet Temperature Face Temperature	Health and Performance
Igniter	Ignition Pulse Detector Cavity Temperature	Operation Verification, Cooling
Regen Liner	Temperature Distribution	Health and Trend (Life) Prediction

TABLE XV

DISPLACEMENT SENSOR REQUIREMENTS

Type	TBD
Range	0.001 to 0.005 inch radial
	0.001 to 0.009 inch axial
Resolution	0.00001 inch
Error Band	± 1.0% of range
Repeatability	± 0.25% of range
Thermal Sensitivity Shift	± 0.005% of range/°C
Temperature Range	-253°C to +100°C
Frequency Response	50 KHZ
Pressure Range	0 to 10,000 psia
Excitation	10 volts DC
Signal	0 to 5 volts DC
Size	TBD
Material Compatibility	
Liquid & Gaseous	Oxygen
Liquid & Gaseous	Hydrogen
Liquid & Gaseous	Nitrogen

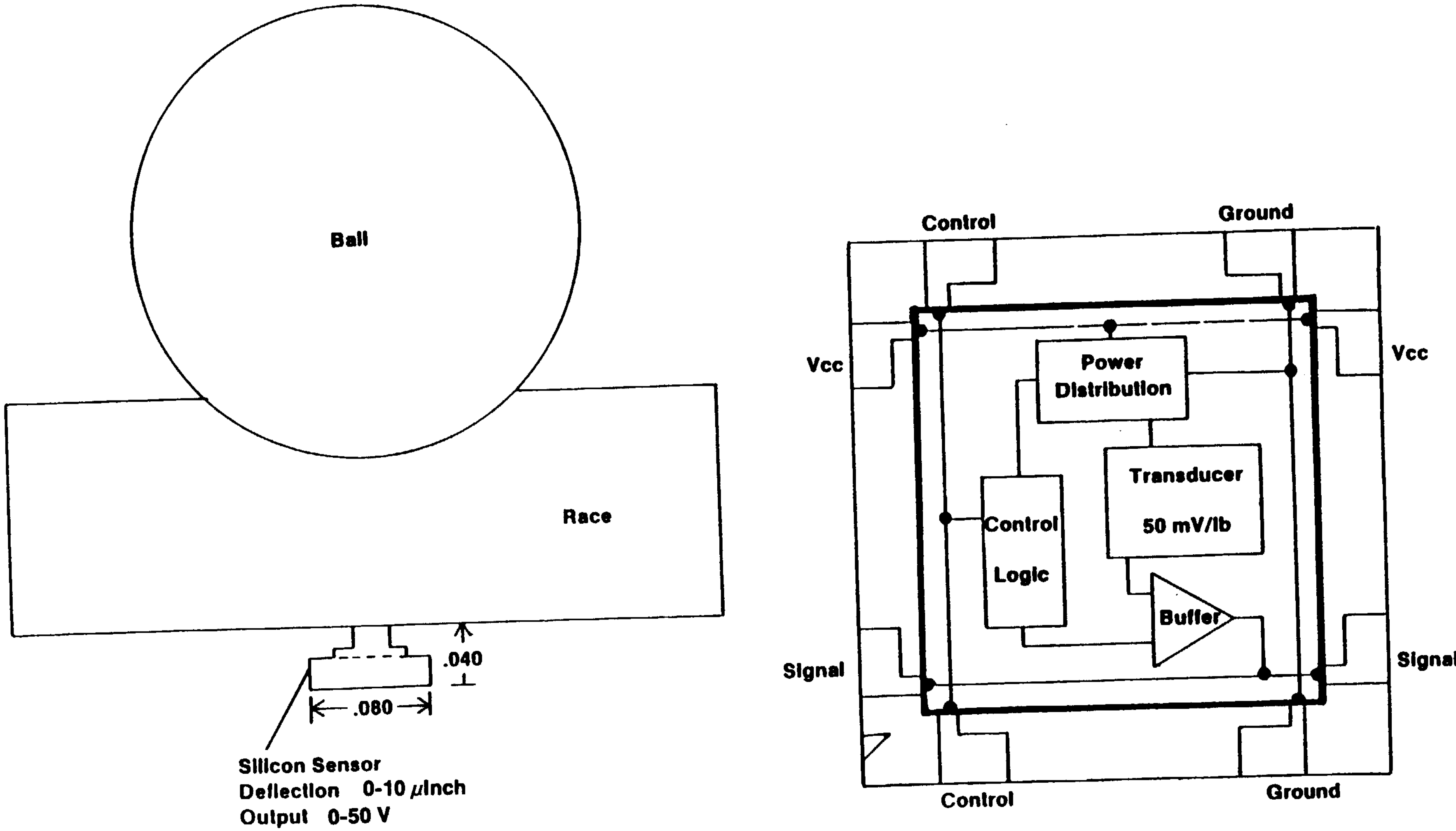
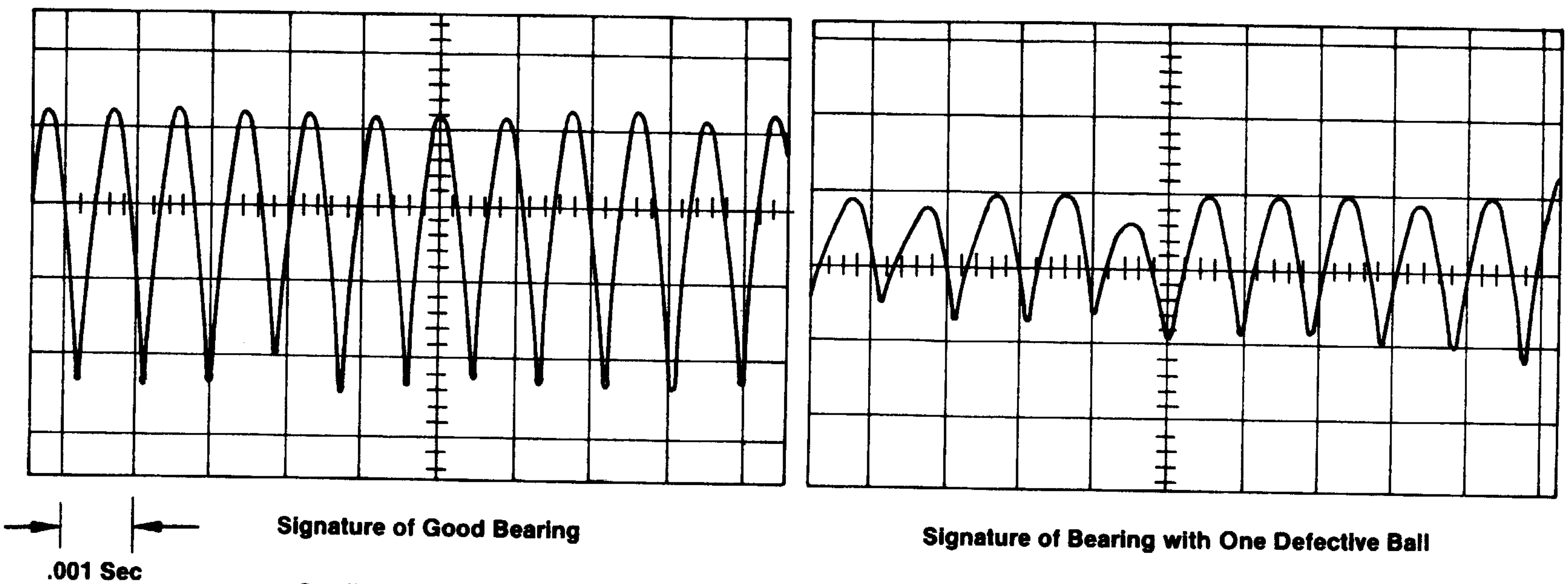


Figure 23. Example of a Bearing Health Monitoring Silicon Sensor



Signature of Good Bearing

- Small Amplitude Variation
- 60,999 RPM

Signature of Bearing with One Defective Ball

- Large Amplitude Variaiton
- 60,000 RPM

NOTE: CRT Presentation Adjusted for Best Signal Clarity. In Both Cases Amplitude is Proportional to Maximum Depth of the Machined Step in the Running Surface. Shaft Cobble Changes the Position of the Trace on the "Y" Axis.

Figure 24. Reproduction of Actual Oscilloscope Traces of Turbopump Bearing Signatures

logic. The current approach involves the use of a multifunction sensor probe for axial and radial displacement and speed. Methods which seem most likely to meet the accuracy and resolution requirements of the application are capacitive, optical (fiberoptic) and inductive. The capacitive transduction method appears to be the most stable under varying environmental conditions as capacitance is a function of the physical dimensions and dielectric constant of the media. A further advantage is that the capacitive sensor tip is the most adaptable to multiple function sensing. A conceptual design based on a three function sensor using capacitive transduction has been prepared and is in development. Figure 25 is the sensor envelope which is designed to fit the oxidizer turbopump. Figure 26 shows the active sensor tip configuration. The sensor tip has three sets of sensing electrodes, one set for radial displacement and two sets for axial displacement. One set of axial displacement electrodes is used for speed pickup when a step is machined into the running surface. The sensing tip is ceramic with metallized electrodes. Signal processing electronics are provided in a semiconductor chip at the sensor tip. Local signal processing is essential to minimize the effects of leakage capacitance.

An electronic hot spot detector for measuring combustion chamber cooling channel temperature is shown in Figure 27. The detector is composed of 120 equally spaced thermocouples (refer to Figure 28 for the sensor configuration). This sensor can be used for the direct detection of local or overall chamber overheating.

H. SENSOR SUPPLIER SURVEYS

ATC has conducted two surveys of health monitor suppliers. The first was a comprehensive survey completed in 1983. The survey data is presented in Figure 29. Approximately 40% of the companies contacted responded. Most of these had product lines closely related to commercial operations and applications. ATC did select 19 suppliers as producing or capable of producing sensors of use in the OTV engine.

The second survey was conducted in February 1987 to assess the available technology for sensing high speed turbopump shaft motion. An initial literature search yielded 122 items related to displacement sensor application. Detailed literature was ordered and evaluated. In addition, the profiles of 151 companies listed in

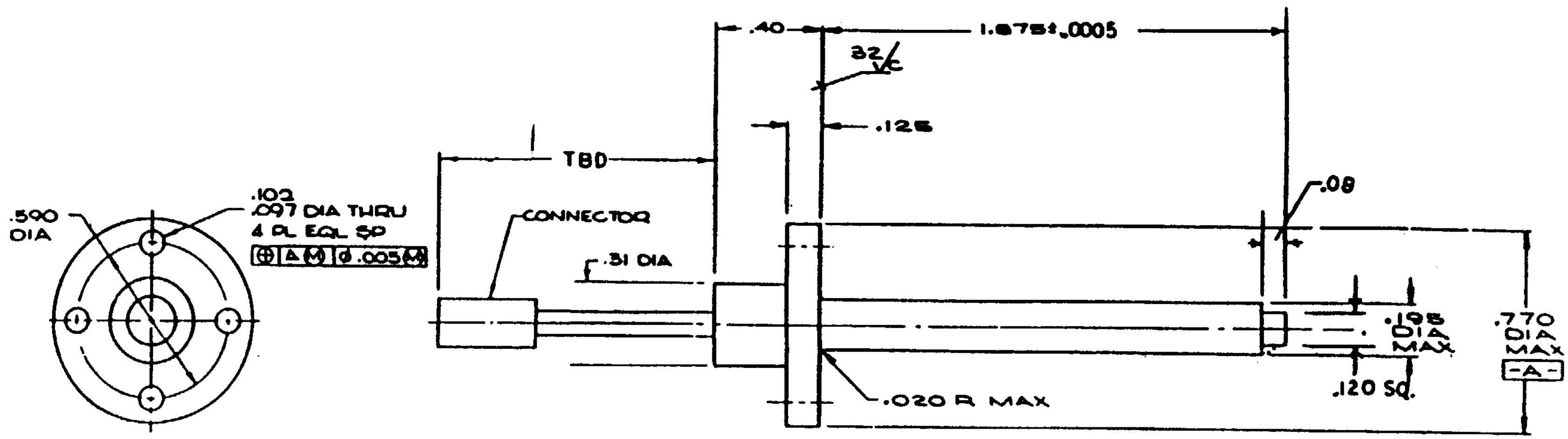


Figure 25. Multifunction Turbopump Shaft Displacement Sensor Longitudinal Section

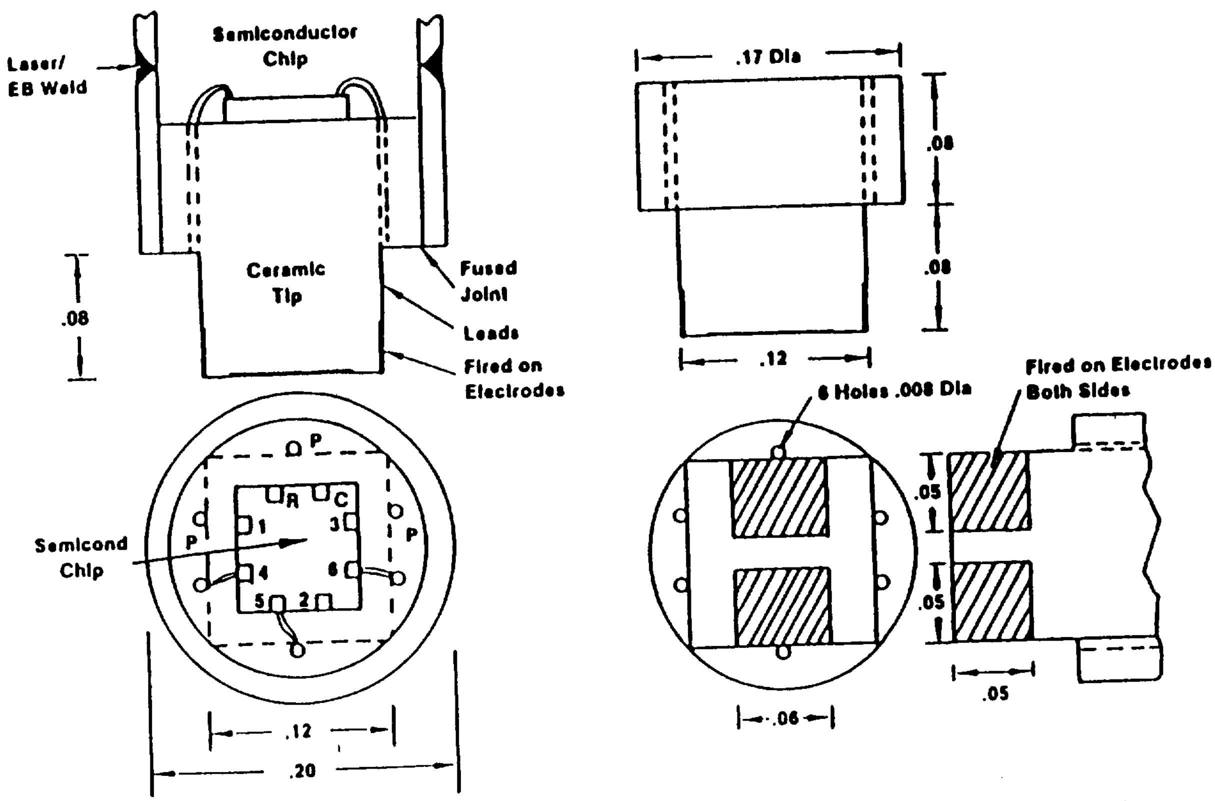


Figure 26. Multifunction Turbopump Shaft Monitor Active Tip Configuration

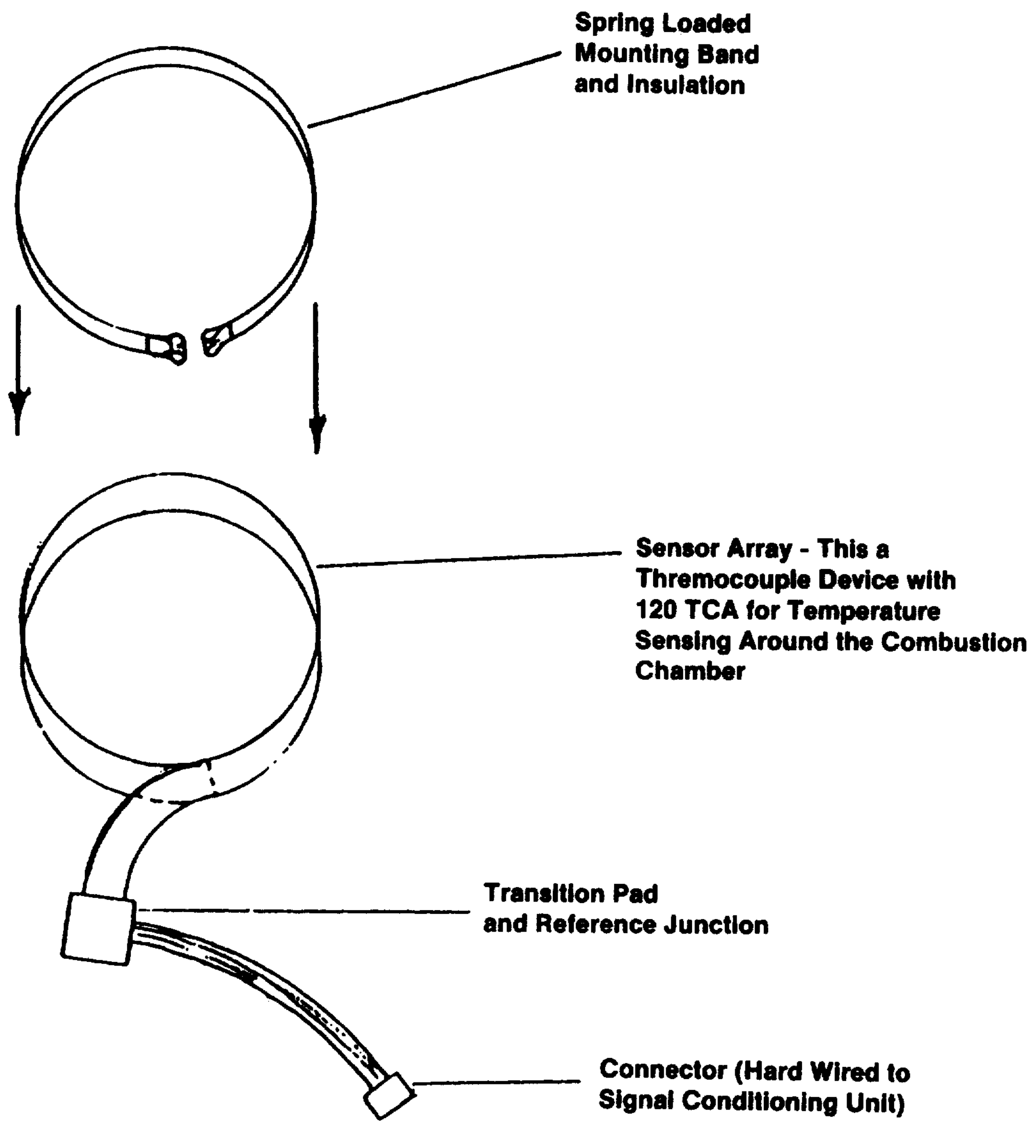


Figure 27. Hot Spot Sensor Assembly

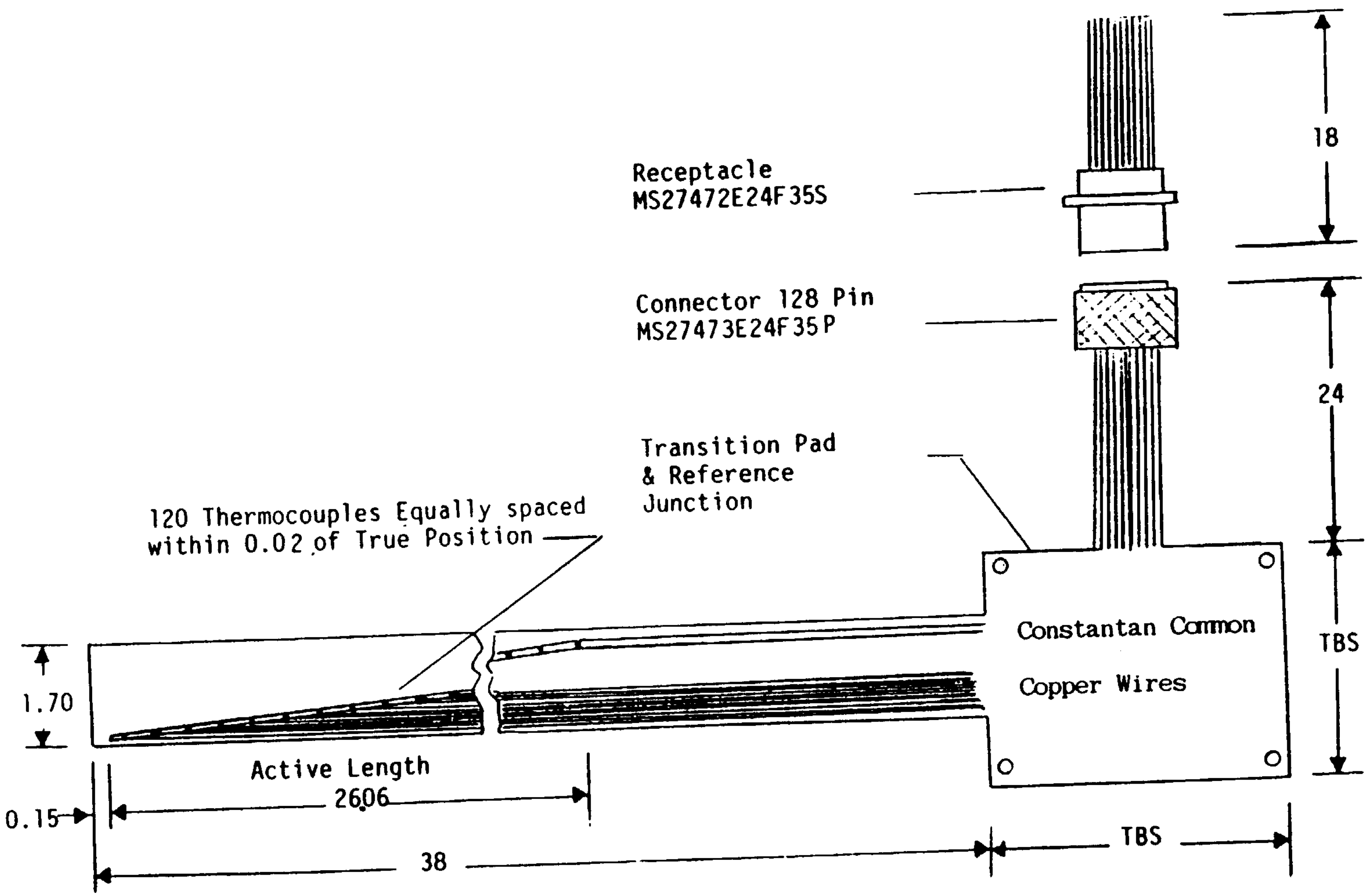


Figure 28. Hot Spot Sensor Configuration

CONTACT BASIS:

Developer/Supplier of Transducers for:

- Acceleration (Angular and Linear)
- Flow (Gas and Liquid)
- Force
- Leakage
- Position (Angular and Linear)
- Temperature
- Velocity
- Other (Torque, Heat Flux, Sound, Stress)

NUMBER OF CONTACTED:

- 242

RESPONSES (As of 26 October 1983):

- 100

ADDITIONAL FOLLOW-UP

- 19 Suppliers

Figure 29. OTV Engine Health Monitoring - Sensor Supplier Survey

the Sensor and Transducer Directory were reviewed. They were all listed as having displacement or proximity sensors in their product line. Inquiries were sent to 50 of these companies asking for information on the following types of sensors:

Displacement, linear
Displacement, mechanical
Displacement, optical
Displacement, ultrasonic
Proximity, magnetic
Proximity, ferrous
Proximity, non-ferrous
Proximity, ultrasonic
Proximity, capacitive

On examination of the literature received from the responding companies, the methods judged most likely to meet the OTV engine turbopump sensor requirements are capacitive, optical (fiberoptics), and inductive. the requirements for a displacement sensor are given in Table XV.

The results of the supplier survey are included as Appendix A.

I. REVIEW OF VEHICLE PRIME STUDIES

The vehicle primes have produced many volumes documenting various concepts and analytical results as a prelude to actual OTV development. Very little of this mass of information is directly applicable to problems of engine control and health monitoring. What is relevant to the propulsion designer are 1) the type of missions in the mission model, 2) total vehicle propellant loads, 3) the type of aerobraking proposed, 4) maintenance concept and timelines (to include delivery, assembly, checkout, disassembly, and preparation for return to earth), and 5) life cycle cost implications. To some extent these mission requirements have been distilled and quantified as the propulsion requirements presented in Table II. The most notable omission is a listing of which engine components should be replaceable in space, and any type of criteria for engine time change. The ATC 3.0K thrust engine was designed for replacement at the engine level with no on-the-vehicle engine maintenance. Thus any anomalous health monitor system diagnosis would

trigger an engine change. This is a very desirable situation for decision making but could be costly if engine changeout required significantly more time than a component changeout.

The present ATC approach recognizes the vehicle Prime contractor's quantification of the high cost of in-space maintenance and the desirability of component versus engine changeout. The 7.5K thrust engine will be designed for some component changeout. These components are listed in Table XVI. This is a fairly long list and may be incomplete at this stage in the engine design. The O_2 and H_2 turbopumps will be designed for changeout in space although it may be more economical to perform the changeout with the engine removed to a specialized maintenance facility at the spaceport. The concern is to preserve the integrity of the lines to and from the pumps. When work will be done with little clearance and with all the restrictions of space suit operation it could prove cheaper to replace an engine than struggle with a difficult component changeout. Timelines must be developed for each maintenance operation to aid in the decision.

The General Dynamics vehicle study did address delivery, assembly, and OTV servicing operations. Table XVII is a listing of the major operations from arrival at the Space Station to payload integration or storage of the OTV. Those operations where the engine health monitor system will be used are indicated by an asterisk. The typical operational scenario for an OTV mission is divided into time sequenced functions as indicated in Table XVIII. The engine health monitor system is used in those functions indicated, as before, by an asterisk. A more detailed outline of the space based maintenance functions is given in Table XIX. The health monitor system will be used for both troubleshooting and verification that the maintenance has corrected the problem.

Of the five items listed above as relevant to the propulsion designer, the most demanding is that of man-rating. The health monitor and control system must assure safe piloted operation of the OTV in so far as this is a function of the propulsion system. If this is built into the design most of the other requirements will be satisfied by straightforward engineering solutions. Low life cycle cost is primarily a function of engine life and overall reliability. ATC is designing for low stress levels on all parts, for wide strength margins in all high temperature

TABLE XVI

OTV ENGINE SPACE MAINTAINABLE COMPONENTS
7.5 LBF THRUST ENGINE

COMPONENT	COMMENT
HYDROGEN MAIN SHUTOFF VALVE	REQUIRES ACCESS NEAR ENGINE/VEHICLE INTERFACE
OXYGEN MAIN SHUTOFF VALVE	REQUIRES ACCESS NEAR ENGINE/VEHICLE INTERFACE
HYDROGEN BOOST PUMP (LOW PRESS)	REQUIRES ACCESS NEAR ENGINE/VEHICLE INTERFACE
OXYGEN BOOST PUMP (LOW PRESS)	REQUIRES ACCESS NEAR ENGINE/VEHICLE INTERFACE
HYDROGEN AUTOGENOUS PRESSURIZATION VALVE	REQUIRES ACCESS NEAR ENGINE/VEHICLE INTERFACE
OXYGEN AUTOGENOUS PRESSURIZATION VALVE	REQUIRES ACCESS NEAR ENGINE/VEHICLE INTERFACE
HYDROGEN REGENERATOR BYPASS VALVE	DESIGN DEPENDENT; MAY BE A BOLT-ON TO A MANIFOLD
OXYGEN REGENERATOR BYPASS VALVE	DESIGN DEPENDENT; MAY BE A BOLT-ON TO A MANIFOLD
GIMBAL MOTORS	REQUIRES ACCESS NEAR ENGINE/VEHICLE INTERFACE
GIMBAL ACTUATORS	REQUIRES ACCESS NEAR ENGINE/VEHICLE INTERFACE
EXTENDIBLE NOZZLE	READY ACCESS
EXTENDIBLE NOZZLE DEPLOYMENT MOTORS	REQUIRES ACCESS NEAR ENGINE/VEHICLE INTERFACE
EXTENDIBLE NOZZLE DEP. MECHANISM	REQUIRES ACCESS NEAR ENGINE/VEHICLE INTERFACE
FUEL FLOWMETERS	DESIGN DEPENDENT; MAY BE BOLT-ON TO LOW PRESS BOOST PUMP
OXYGEN FLOWMETERS	DESIGN DEPENDENT; MAY BE BOLT-ON TO LOW PRESS BOOST PUMP
CONTROLLER	ONE OR TWO REMOVABLE BOXES WITH CANNON PLUGS
SENSOR SIGNAL CONDITIONING UNITS	DESIGNED TO ALLOW SENSORS TO REMAIN IN PLACE, ONLY ELECTRONICS CHANGED (REQUIRES SYSTEM RECALIBRATION)
MISCELLANEOUS HARDWARE, BRACKETS, WIRES, EXTERNAL SENSOR ELEMENTS	DEPENDENT ON ACCESS

TABLE XVII

INITIAL OTV DELIVERY AND ASSEMBLY OPERATIONAL FUNCTIONS

Dock Shuttle to Station

- Offload and position core section
- Offload aerobrake, struts, aerobrake door, and RCS thrusters
- Deploy aerobrake
- Attach RCS thrusters, aerobrake, and aerobrake door
- Inspect OTV assembly

Checkout OTV System

- Bring all systems online*
- Perform OTV system operational testing*
- When fault or damage detected*
    - Perform damage assessment
    - Initiate fault isolation routine
    - Perform OTV unscheduled maintenance
    - Perform OTV system operational testing
- Proceed with payload integration or deactivate and stow OTV

*Operations where the OTV engine health monitor system is used

TABLE XVIII

OTV SERVICING OPERATIONAL FUNCTIONS

BERTH OTV
- RENDEZVOUS OTV WITH STATION
- CAPTURE OTV AT STATION
- BERTH OTV AT STATION

TRANSFER PROPELLANT
- VERIFY INTERFACE INTEGRITY
- PERFORM PROPELLANT LEAK CHECK
- TRANSFER RESIDUAL PROPELLANT FROM OTV STATION

INSPECT OTV
- PERFORM VISUAL INSPECTION
- DETERMINE OTV FAULT STATUS*
- WHEN FAULT OR DAMAGE DETECTED*
  - PERFORM DAMAGE ASSESSMENT (TV/EVA)
  - INITIATE ELECTRICAL TEST ROUTINE TO VERIFY FAULT
  - INITIATE FAULT ISOLATION ROUTINE
- FORMULATE INTEGRATED MAINTENANCE PLAN*

PERFORM OTV MAINTENANCE
- PERFORM SCHEDULED/UNSCHEDULED MAINTENANCE TASKS*
- MISSION RECONFIGURE
- PERFORM SYSTEM OPERATIONAL TESTING*
- DEACTIVATE & STOW OTV (IF NOT REQUIRED FOR MISSION AT THIS TIME)

MATE OTV & PAYLOAD
- TRANSFER PAYLOAD TO OTV
- MATE PAYLOAD TO OTV
- VERIFY OTV/PAYLOAD INTERFACE
- PERFORM OTV/PAYLOAD INTEGRATION TEST

LAUNCH OTV/PAYLOAD
- PERFORM PRELAUNCH OPERATIONS*
- TRANSFER PROPELLANT FROM STATION TO OTV
- LAUNCH OTV/PAYLOAD*

*OPERATIONS WHERE THE OTV ENGINE HEALTH MONITOR SYSTEM IS USED

TABLE XIX

SPACE-BASED OTV MAINTENANCE FUNCTIONS

Perform scheduled maintenance

- Transfer propellant to and from OTV
- Perform visual inspection
- Determine OTV fault status
- Replace ACS modules (after each mission)
- Replace engine module* (after TBD mission time)
- Perform system operational testing
- Service fuel cell (after TBD mission time)

Perform unscheduled maintenance

- Perform damage assessment (beyond scheduled inspection)
- Verify electrical failure
- Isolate fault to replaceable unit
- Perform damage repair
- Perform required remove and replace due to failure

----

*The vehicle can be developed with replaceable propulsion modules or for individual engine replacement. In-space handling requirements may dictate one or the other design solution. Table XX lists the steps in removing an engine in Aerojet's design concept.

TABLE XX

OTV ENGINE REMOVAL OPERATIONS

- Engine Centered, Nozzle Extended
- Propellant Isolation Valves Closed
- Electrical Power Removed from the Engine
- Manual Operations:
  - Electrical Harness Disconnected, Cannon Plugs Capped, Harness Stowed
  - Extendible Nozzle Removed, Screw Assemblies Secured, Regen Cooled Nozzle Edge Protector Installed
  - Main Hydrogen Line Disconnected Below Shutoff Valve, Capped
  - Main Oxygen Line Disconnected Below Shutoff Valve, Capped
  - Hydrogen Tank Autogenous Pressurization Line Disconnected Below Shutoff Valve, Capped
  - Oxygen Tank Autogenous Pressurization Line Disconnected Below Shutoff Valve, Capped
  - Engine Handling Fixture Connected
  - Engine Out Gimbal Actuator Disconnected
  - Control Gimbal Acuators Disconnected
  - Flex Lines Restrained, Upper Engine Covered with Protective Material
  - Prime Mover Connected to Engine Handling Fixutre
- Engine Moved out of Engine Compartment

materials, and the generally conservative design selections that accompany high reliability. The basic control system will be proven on an operational rocket engine 15 years before it is flown on the OTV engine. The health monitor sensors will all have a pedigree that includes a wide range of missions and test conditions. This design approach should give the lowest life cycle cost and the safest operation for a piloted space vehicle.

VII. DISCUSSION OF RESULTS

A. ENGINE CONTROL AND MODELING

A variety of control simulations of the dual expander engine design were successfully run, but project changes and resource constraints precluded performing simulations over the entire operating envelope. Such simulations would need to be run if work continues in developing the dual expander cycle engine. Also, the component models used in the simulations can and should be updated as component development proceeds.

The results of the control simulations using the TUTSIM program were acceptable even though more cases would have been desirable. In both throttle-up and throttle-down scenarios the proposed control valve arrangement performed within acceptable limits of mixture ratio and thrust excursion. There was no set-point hunting, and transitions were free from spikes or short term oscillations. The concept of mechanically separate turbopumps for this engine is practical from a controls standpoint from the pumped idle point to some overthrust point above the nominal 7500 lbf of thrust. What could not be proven in the controls simulation is the practicality and controllability of a tank head start. With the very low pressure available (15 psia) for a tank head start actual components, as built versus as designed, can seriously effect operating margins. No one can guarantee a successful tank head start for an engine of this complexity until actual components are built and tested; even then, start-to-start repeatability will be questionable and subject to lack of success from even small changes in system fluid properties or temperatures of components.

Engine shutdown is a much more straightforward operation. The main propellant valves are simply closed and residual propellants allowed to burn to a pressure where combustion is no longer sustained. The relatively large line and component volumes will produce a tailoff impulse lasting 2 or 3 seconds. Both startup and shutdown are slow compared to storable propellant rocket engines where these transient conditions are measured in milliseconds.

There is a maximum time-rate-of-change for throttle commands that must be compatible with mission requirements. If the most demanding mission is a landing on the moon or Mars then this is calculable once the vehicle weight and number of engines are determined. This should be done early enough in the engine development to establish it as a controls requirement. Otherwise it could become a mission limitation or an expensive problem needing solution. This controls analysis did not attempt to assess the maximum throttle rate with the baseline control system.

The software package used for this simulation, called "TUTSIM," is in widespread use but has several limitations. A major one is incompatibility with frequency domain analysis techniques. It is also primarily adapted for personal computers and the limitations in processing speed and memory of PCs. A mainframe software package such as MATRIX-X includes all linear system analysis functions including interactive classical and modern control design, conversion between model forms, and computation of time and frequency responses. It should be considered for any future extension of this controls modeling work. It was just recently added to ATC's library of programs; too late to be used in this task.

B. CONTROL ELEMENTS

The basic control elements are valves, flowmeters, pressure and temperature sensors, turbopump speed sensors, and an electronic controller. In the integrated approach sensor data from an additional array of sensors supplements the control sensor data to allow a health management software/firmware system to evaluate engine health and, if necessary, direct a specific controller action. It can also synthesize data for the controller should some control sensor(s) be inoperative. The desired result is a more flexible control system with greatly improved safety and reliability. Work done in this task tends to confirm this as an achievable goal in so far as the mechanical control elements are concerned. Valves can be developed and sensors obtained without any major technology challenges to the OTV engine development. Development work is needed on turbine bypass valves. Sensors need to be miniaturized while reliability is improved. Those are achievable with

logical extensions of present technology; no breakthroughs are needed. This is not necessarily true of the software/firmware that takes the sensor data and processes it to predict engine health and diagnose engine problems. This will be a significant development task and one that may require artificial intelligence software for best applicability to the task. It is worthy of separate consideration as a development task. The work done here on sensors and system architecture can serve as a good starting point.

C. HEALTH MONITORING

Health management comprises three separate tasks: real time monitoring of engine health; and recording of information for a permanent maintenance record with guidance on component changeout, recalibration, and troubleshooting, and an intelligent selection and processing of data streams. Health management must be done with the speed needed to prevent imminent failure from becoming catastrophic. It is evident that computational requirements are high and programming an extensive process. The basic engine controller can be readily developed from well advanced work on a bipropellant engine controller at ATC. The interacting health management system is not well defined in terms of hardware. It should be an electronic box much like the controller, mounted adjacent to it, have direct connection to the Health Monitor sensors, and have a remotely located recording unit accessible to both vehicle crew and maintenance. The form taken to record its programs is uncertain as is the memory storage. It will be a very sophisticated computer, and should be a candidate for early development work.

VIII. SUMMARY OF RESULTS

This report documents the first extensive work done in defining an integrated health management and control system for the Orbit Transfer Vehicle (OTV). The work was divided among four subtasks: 1) engine system modeling, 2) control logic evaluation, 3) control element requirements, and 4) health monitoring. The task work led to the following conclusions:

1. Engine System Modeling

a) There is a maximum time-rate-of-change for throttling operation, but additional work needs to be done to define it.

b) Changes in the details of the engine schematic need to be modeled and incorporated into the system model to assure controllability and stability are maintained as the design evolves.

c) Additional work needs to be done to tune the systems so that the linear and nonlinear models match.

d) The most poorly defined engine operation is tank head start. The low pressure budget makes actual equipment variables critical in defining whether it is possible. Actual tests will be needed to prove its feasibility.

2. Control Logic Evaluation

a) The baseline engine control system can control thrust and mixture ratio from pumped idle mode to some thrust above nominal.

b) Mechanically separate hydrogen and oxygen turbopumps can be used for normal fixed thrust operation and throttling operations.

c) The control logic evaluation showed that turbine bypass valves could control thrust and mixture ratio as planned over most of the thrust range using flowmeter data. At low thrust conditions, flowmeter data may have to be supplemented with turbine speed readings to assure that mixture ratio does not exceed allowable limits if only one pump should rotate.

d) Closed loop control configuration is required for the OTV engine. There is no capability for a start without a functioning controller.

e) Control system stability was achieved at all the operating points checked, but additional work needs to be done to assure that the system was stable over the entire operating range. In particular, the range where the oxygen turbine bypass control effects are non-linear needs to be assessed.

f) A preliminary failure-mode and effects analysis (FMEA) was completed for the baseline controls configuration.

g) A reliability assessment was completed in terms of design impact. This report recommends analytical redundancy wherever possible instead of hardware redundancy.

h) Control of this engine is considered verified on a preliminary basis,but additional work should be done concurrent with a test bed program.

i) An integrated approach to health management and control is considered practical with this report serving as a starting point for follow-on work.

3. <u>Control Element Requirements</u>

a) The basic control elements of valves, flowmeters, and sensors have been identified and well enough specified to begin procurement or detail design actions.

b) An ATC developed controller was evaluated for the controller requirement and was found to be acceptable with some modifications. This could be a significant savings in an engine development program.

c) A sensor supplier survey was completed and the results presented. All expected sensor needs can be met with development programs well within the engine development time span.]

4. Health Monitoring

a) The health management system was defined in sufficient detail that sensors were identified, a system architecture was developed, and a data recording system proposed. This is sufficient definition to be used as the baseline for a detailed design or to assist in defining requirements for a health management system software development program.

b) Prime contractor vehicle studies were reviewed and health management related activities identified. The system will be used for pre-flight, post-flight, and permanent maintenance record purposes based on Prime identified operations.

c) A component in space maintenance list was developed but no timelines were available for evaluating the practicality of component changeout. The alternative of complete engine removal was presented and a list of steps in the changeout included. The basic maintenance philosophy needs to be defined after considering the timelines and extra-vehicular activity (EVA) costs.

IX. REFERENCES

1. Anon, Orbit Transfer Vehicle (OTV) Advanced Expander Cycle Engine Point Design Study. Contract NAS 8-33574 Final Report. Aerojet Liquid Rocket Co. report no. 33574-F for Marshall Space Flight Center, December 1980.

2. Turnaround Operations Analysis Report for OTV, Vol. I, II, III, and IV, Contract NAS 8-30924 Final Report. General Dynamics Space Systems Report No. GD55-SP-87-018, for NASA Marshall Space Flight Center, February 1988.

APPENDIX A

SENSOR SUPPLIER SURVEY RESULTS

SURVEY OF AVAILABLE SENSOR TECHNOLOGY

In order to identify and evaluate approaches to measure axial and radial shaft displacements of high speed turbomachinery, a survey of available technology was undertaken. The objective of this survey was to determine the current state-of-the-art for displacement sensors, their capabilities and applicability to the OTV turbomachinery.

A library literature search was made yielding 122 items. The literature covered a wide range of transducer subjects including inductive, capacitive, ultrasonic, optical, and fiberoptic devices. Those that appeared pertinent were obtained and reviewed.

Profiles from 151 companies listed in the "Sensor and Transducer Director" which listed displacement or proximity sensors in their product line were reviewed. Inquiries were sent to 42 companies from this list which appeared to have applicable technology. Most of the responses described devices and technology that were for industrial applications and did not have the accuracy and resolution needed. Examples of some of the commercially available displacement measuring instruments which most nearly meet our requirements are shown on Table A-1. Included in this investigation are the following displacement measuring technologies:

1) Inductive
2) Capacitive
3) Optical
4) Ultrasonic

The following assessments were made of the available technologies based on past experience combined with the results of this investigation:

Inductive

Inductive displacement sensors measure the distance from the sensor to the target by generating a high frequency magnetic field. As the target moves toward the sensor coil eddy currents are generated in the target material which show up as losses in the oscillator bridge network. The variations in losses or distance are

Table A-1
Displacement Measurement Instruments

Type	Manufacturer	Range Mil	Resolution Mil	Accuracy	Size inches	Temp. Range °F	Output	Freq. Response	Comments
Inductive	Bently Nevada Corp. Minden, Nevada	70		± 1%	0.2 dia 0.8 Lg	-30 - +350	200 mv/mil	10kHz	Requires signal conditioner (proximitor) Size 2.0x2.4x3.1 in. Larger size probes avail.
Inductive	Metrix Instrument Co. Houston, TX	80			0.19 dia 1.26 Lg	-35°C - +175°C	200 mv/mil	3kHz	Requires signal conditionr. Used 1mHz excition to probe.
Inductive	Kaman Inst. Co. Colorado Springs, CO	10	0.004	± 1/2%	0.08 dia 0.81 Lg #10/32THD	-65°F - +300°F	100 mv/mil	50kHz	Requires signal conditioner. Several probe sizes available. Thermal sensitivity shift 0.008 mil/°F
Inductive	Scientific-Atlanta, Inc., Atlanta, GA	80			0.19 dia 0.75 Lg	-30 - +350°F	200 mv/mil	50kHz	Requires signal conditioner
Capacitive	ADE Corp. Newton, MA	3 to 9	1×10^{-3}	± 0.4%	0.10 dia Tip 0.280 x 1.0 lg overall		± 10 vdc Full Scale	40kHz	Probe contains 4 diodes and is excited from 3kHz driver. External linearization circuits req'd. Min. electrode dia = 0.019 in.
Capacitive	MTI Inc. Latham, N.Y.	0.25 to 10	10×10^{-3}	± 0.4%	.25 x 2.5 in.	-200°F - +400°F	± 10 vdc	5kHz	Special coax cable req'd. No electronics in probe. Higher resolution for smaller range.
Fiberoptic (Lever)	MTI Latham, N.Y.	0.002 to 0.0055	1.4×10^{-3}	± 5%	0.063 in. x 3.0 in.	-100 - 300°F	6	60kHz	Probes available to .020" diam. with lesser performance
Fiberoptic (Lever)	EOTec Corp. West Haven, CT	≈.005	.06 min/mv		.285 dia x .95 in. lg		0-10 volts	5kHz	
Laser Triangulation	Diffracto, Ltd. Troy, MI	0.080	4×10^{-2}	±1.25%	6 x 3.4 x 1 in.			200/sec	2 inch standoff distance required

detected and used as a measurement of displacement. A typical block of the sensor system is shown in Figure A-1.

Inductive sensors are widely used for displacement sensing in industrial applications and machinery. ATC has used them successfully in rocket engine turbomachinery for non-cryogenic applications. Sensors are available as small as 0.08 in. dia x 0.8 in. long. Larger diameter sensors measure larger displacements. Output is typically 200 mv per 0.001 inch. Frequency response is as high as 50KHz for some units.

Some of the factors affecting the indicated displacement are:

(a) Target material resistivity and permeability
(b) Proximity of sensing tip to conducting material
(c) Temperature of sensor
(d) Temperature of target

Multiple sensors in close proximity to each other can cause crosstalk and noise which will diminish their accuracy.

Our recent experience in using inductive sensors at liquid nitrogen temperatures (-320°F) has indicated erratic behavior with large signal changes under constant displacement conditions. In another case where sensors were designed specifically for use in liquid hydrogen the performance appears to be better. The initial calibration shows fairly good linearity from 0.005 to 0.0015 inches. Zero shift is from zero to 0.003 inches from temperatures of -320°F to -411°F. To be useful the operating temperature must be known continuously and calibration curves at the appropriate temperature must be available or a temperature compensating signal conditioning unit is needed.

Factors affecting calibration are:

(a) Coil resistance and temperature coefficient
(b) Target material resistivity and temperature coefficient
(c) lead resistance variations

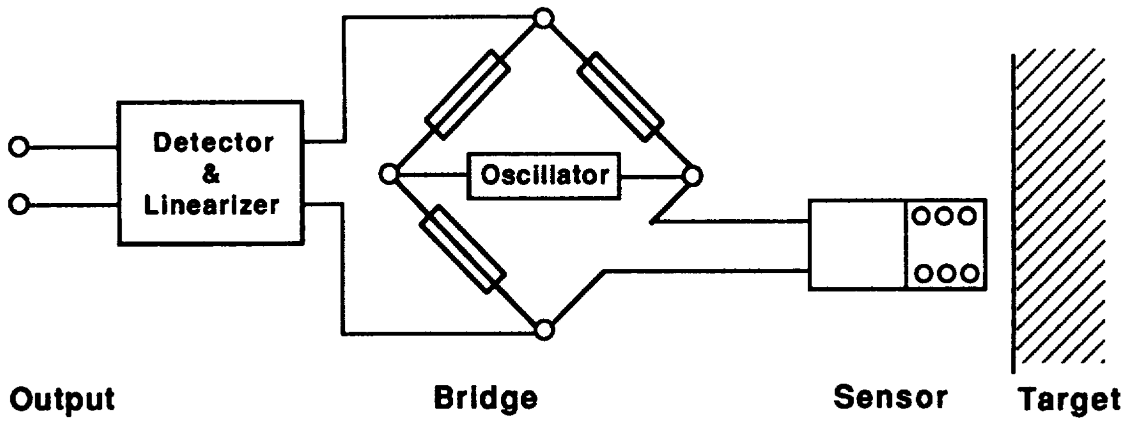


Figure A-1. Displacement Sensor Schematic

Capacitive

Capacitance displacement sensors use the capacitance between the sensor electrode and the target as a measure of distance. The circuit capacitance is inversely proportional to the distance between the sensor electrode and the target. Because the measured capacitance is very small (in the picofarad range) it is necessary to eliminate the effect of probe and lead leakage capacitance which can be many times the measured capacitance. Several signal conditioning approaches are used to try to meet this objective. Figure A-2 lists the characteristics of two commercially available capacitive instruments capable of precision measurements. The ADE instrument excites the capacitive sensor with a high frequency (3mHz) driver to provide a current proportional to the tip capacitance. The current is rectified by four diodes in the sensor tip to provide a D.C. output for displacement measurement. By placing diodes in the sensor tip leakage capacitance effects are minimized and the output signal is D.C. Frequency response of 50KHz is claimed with resolution better than one microinch for sensor target separation in the range of 0.010 inches. Standard sensor probe diameters as small as 0.280 inches are available. No cryogenic temperature performance is claimed; however, with rectifying diodes as the only temperature sensitive elements in the probe tips performance could be expected to be as good as the available diodes for cryogenic service.

The MTI instrument is an example of another capacitive displacement instrument. This instrument has no active electronics in the sensor tip and uses a guarded circuit to eliminate the effects of stray and cable capacitance. The sensor configuration is shown in Figure A-3.

For a range of 0.01 inches its resolution is 10 microinches. Frequency response is 5kHz maximum. Standard sensor diameter is 0.25 in. for a 10 mil range.

Optical

Optical displacement sensors use light reflected from the target as a means of measuring displacement. To obtain high resolution and accuracy special provisions are required. Some laser-based systems use triangulation to obtain displacement. These systems are usually bulky and not suitable for aerospace applications.

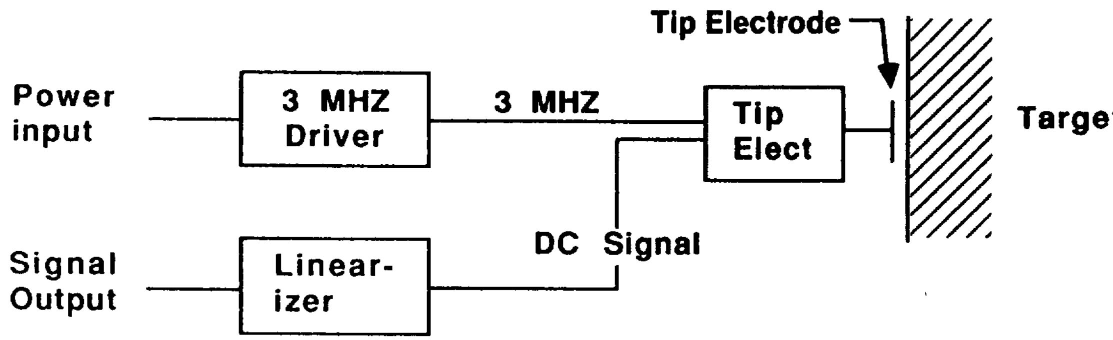


Figure A-2. Block Diagram of Capacitive Sensor

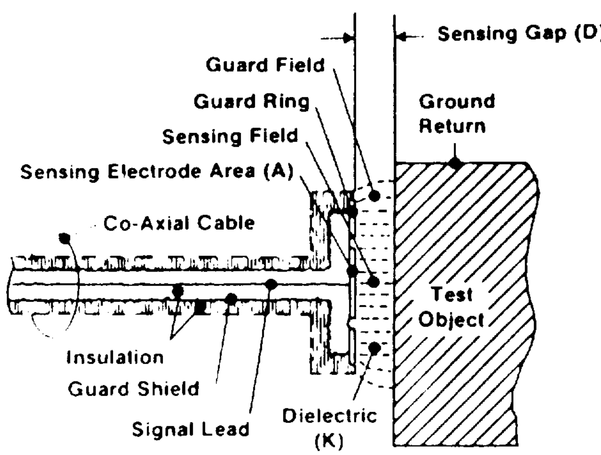


Figure A-3. MTI Sensor Configuration

One unique system which takes advantage of fiberoptic technology is represented by an instrument manufactured by MTI. It measures light reflected from the target through a bundle of optical fibers. The arrangement is shown in Figure A-4. The sensor system utilizes adjacent pairs of light transmitting and light receiving fibers. The basis for the sensing mechanism is the interaction between the field of illumination of the transmitting fibers and the field of view of the receiving fibers. At contact with the target no light is provided to the receiving fibers. As the gap is increased a rapid increase of light to the receiving fibers is realized until an optical peak is reached. Beyond that gap the light reflected to the receiving fibers decreases according to a square function.

This system provides resolution in the microinch range with sensors as small as 0.063 diameter. Sensors have been made as small as 0.020 diameter with some loss in resolution. Problems due to differential expansion of the fiberoptic bundle and the metal sheath have occurred at cryogenic temperatures. Variations in surface reflectance and media opacity will result in measurement errors. In addition, accurate measurements are difficult to achieve without on-line gap adjustments.

Ultrasonic

Ultrasonic displacement transducers measure distance by reflecting high frequency acoustic energy from the surface of the target and measuring the transit time. These systems have a resolution capability in the range of 0.001 in. which is inadequate for measuring rotor dynamics of high speed turbomachinery. In addition, media temperature variations can introduce significant errors as sonic speed is a function of temperature.

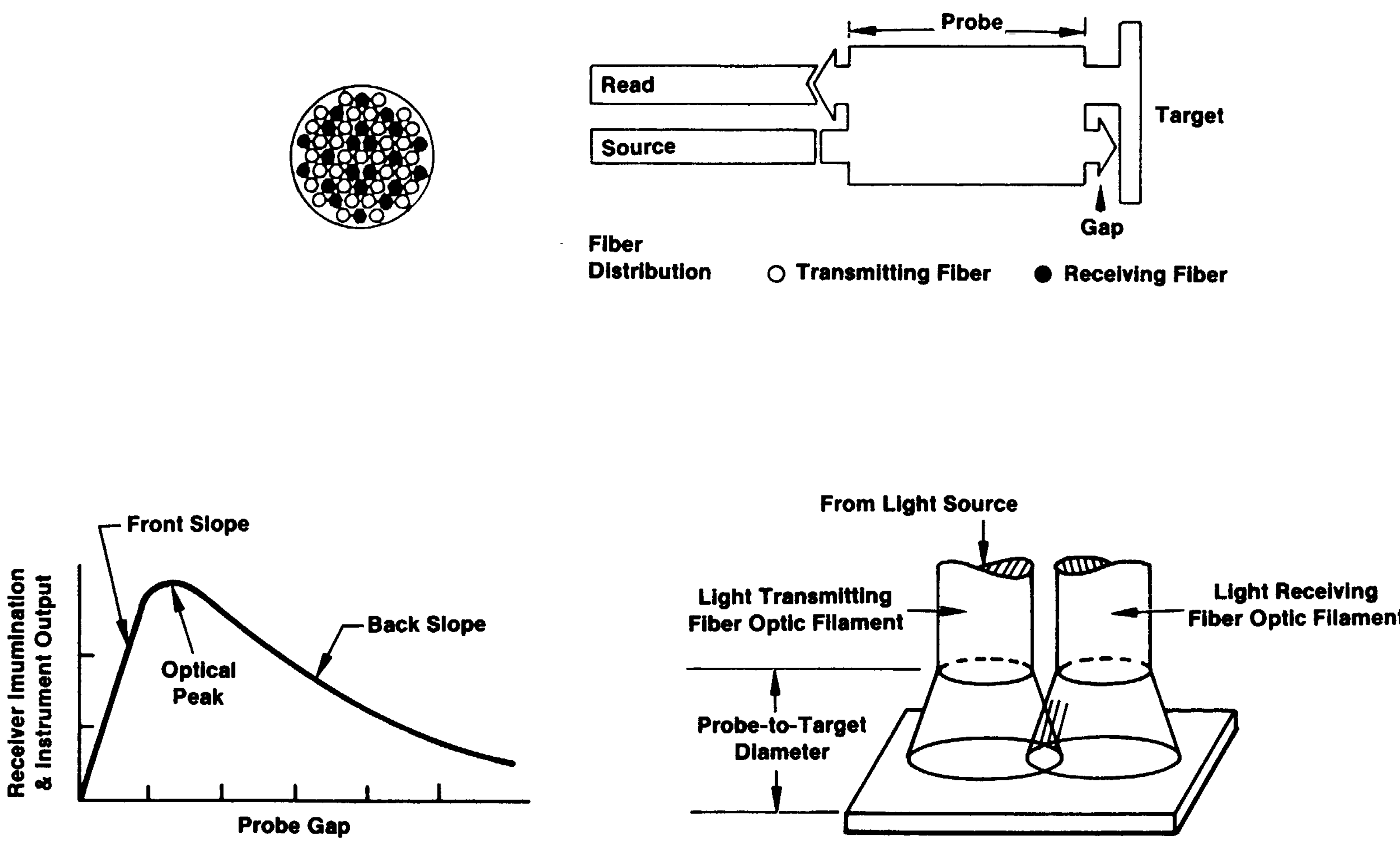


Figure A-4. Fiberoptic Sensor Operation

APPENDIX B

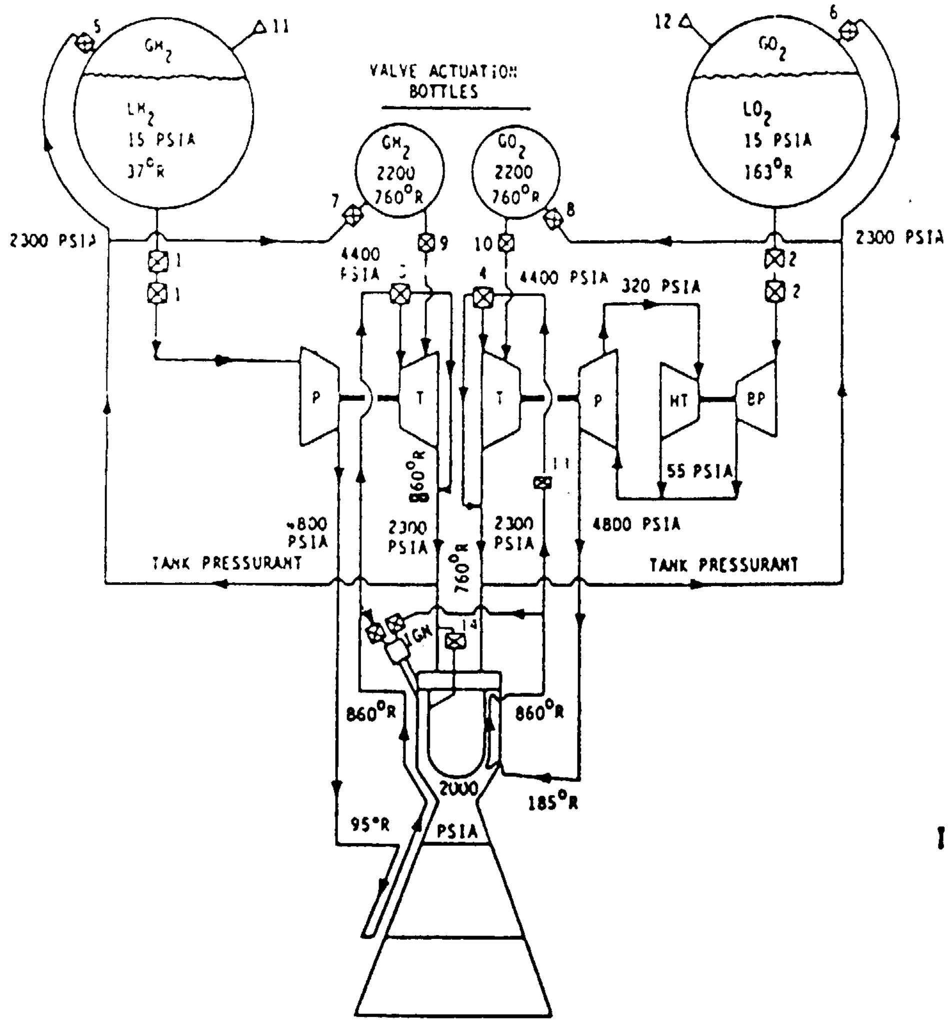
PRELIMINARY VALVE AND SENSOR SPECIFICATIONS

Preliminary Valve Specifications

This integrated controls and health monitoring project was started while the baseline Aerojet version of the OTV engine was a 3000 lbf thrust dual expander cycle engine. The task was completed after a NASA directed change to the baseline engine thrust was made. The new 7500 lbf thrust engine retained the basic dual expander cycle but engine design activities produced a number of changes to the propellant routing and valves. The original 3K lbf thrust engine schematic is given in Figure B-1. The later version of the 7.5K lbf thrust engine is given in Figure B-2. All specifications for valves are keyed to the requirements of the 7.5K lbf thrust engine. The specification sheets also contain an envelope diagram giving general dimensions for use in layout drawings and initial valve procurement action. These specifications were developed in the engine preliminary design task, and details on criteria and selection will be available in the report for that task. Valve specifications sheets are given as Figure B-4 through B-16.

Preliminary OTV Engine Sensor Requirements

OTV engine sensor requirements were thoroughly reassessed during the engine preliminary design task. Figure B-3 is a schematic of the most recent configuration for the 7500 lbf thrust baseline engine showing sensor locations. This compilation of the sensors proposed for each engine includes those for the nozzle extension and its deployment mechanism and engine compartment sensors not actually installed on the engine but vital to determining safe engine function. The only sensors specific for engine control are the flow meters although the engine controller makes use of a variety of other sensor data. The sensors are divided into two groups: HM-1 for primary functions, and HM-2 for health monitor assessment and backup to the HM-1 group. This list is the result of a pre-screening of candidate sensors, but there was no concerted effort to reduce sensor numbers to any specific figure. Characteristics of the sensors are given in Table B-1. This includes estimates on sensor weight and power requirements. The function of the sensor is given according to priority. When sensor output is used by the engine controller this is the primary function although the data may also be used for health monitoring purposes.



BP - BOOST PUMP
HT - HYDRAULIC TURBINE
P - PUMP
T - TURBINE
1 - LH_2 SHUTOFF VALVES
2 - LOX SHUTOFF VALVES
3 - TURBINE BYPASS VALVE GH_2
4 - TURBINE BYPASS VALVE GO_2
5 - GH_2 PRESSURIZATION CHECK VALVE AND REGULATOR
6 - GOX PRESSURIZATION CHECK VALVE AND RETULATOR
7 - GH_2 START BOTTLE CHECK VALVE
8 - GO_2 START BOTTLE CHECK VALVE
9 - GH_2 TURBINE START VALVE
10 - GO_2 TURBINE START VALVE
11 - LH_2 TANK VENT VALVE
12 - LO_2 TANK VENT VALVE
IGN - IGNITION SYSTEM
13 - OXIDIZER BACKPRESSURE VALVE
14 - FUEL FILM COOLING VALVE

Figure B-1 Dual Propellant Expander Engine

ORIGINAL PAGE IS
OF POOR QUALITY

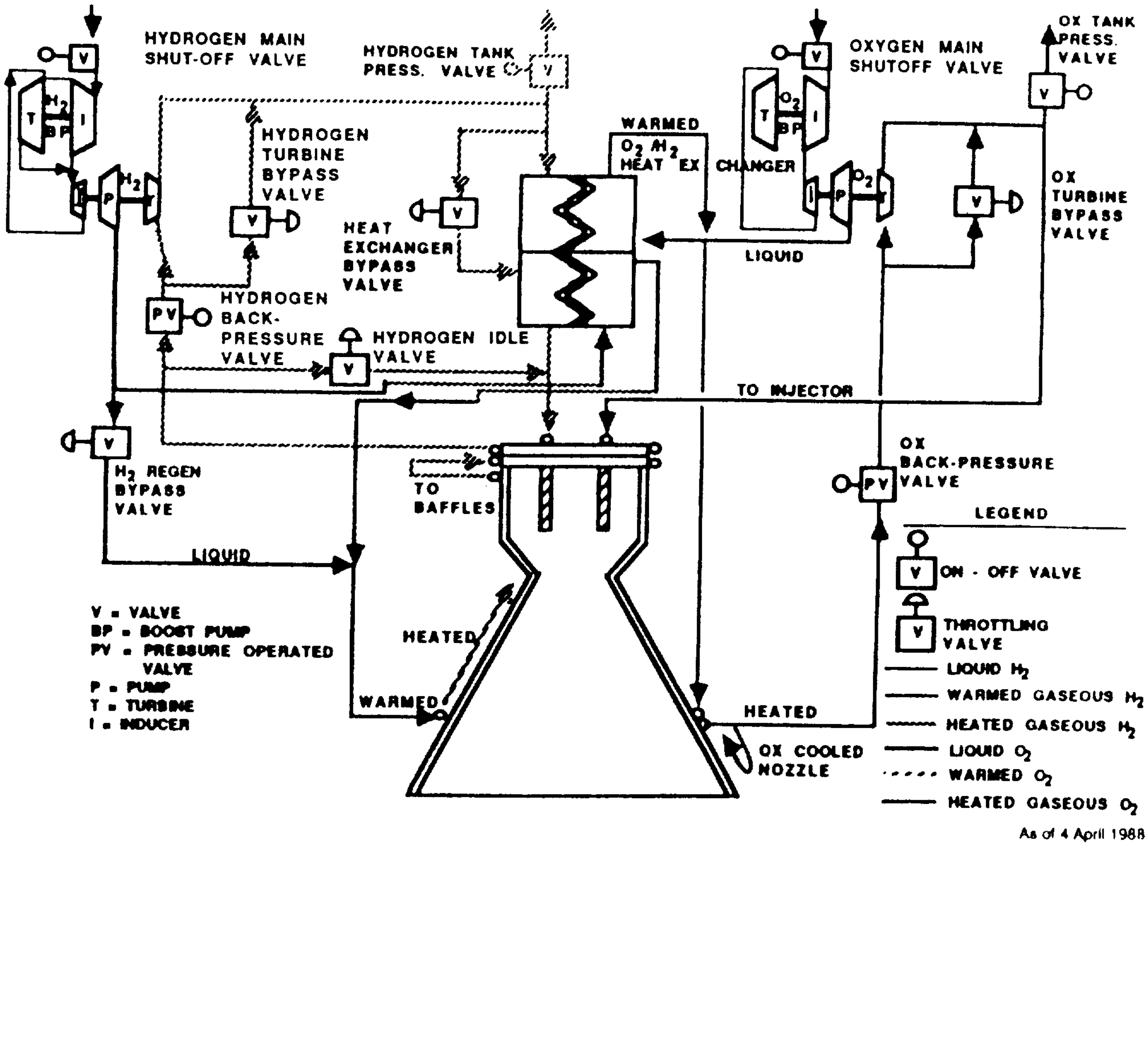


Figure B-2 7500 lbs Thrust OTV Engine Dual Expander Cycle

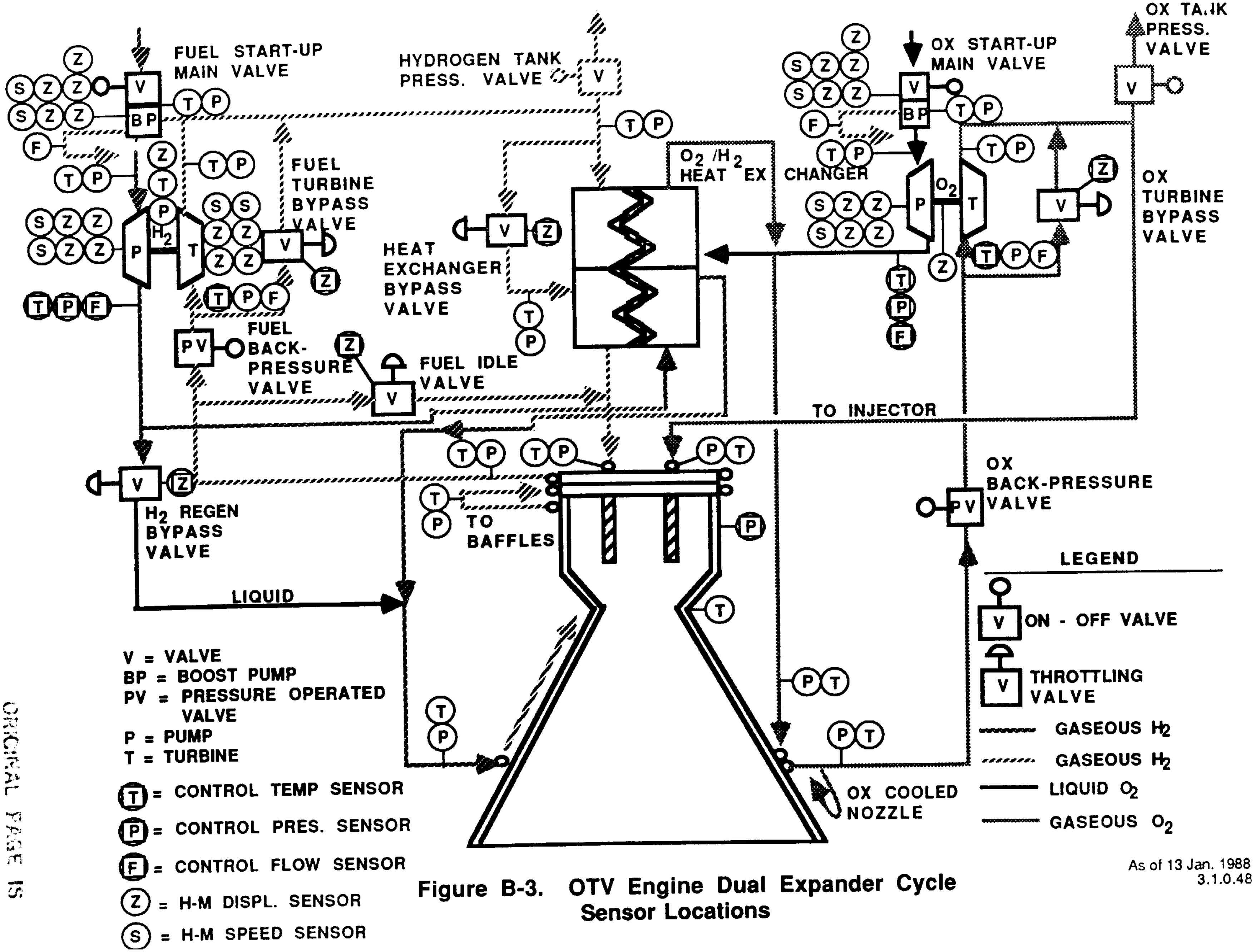
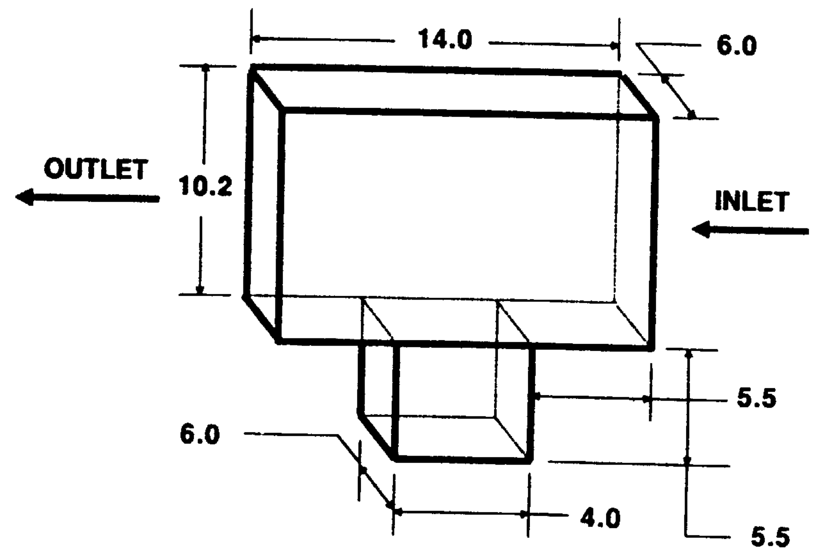


Figure B-3. OTV Engine Dual Expander Cycle Sensor Locations

As of 13 Jan. 1988
3.1.0.48

VALVE FUNCTION :	HYDROGEN MAIN SHUT-OFF
VALVE TYPE :	N.C.,ON/OFF,BALL;BFLY;BLADE
ACTUATION METHOD :	28 VDC MOTOR
EST. POWER REQ. :	165 WATTS
EST. WT. (+-20%):	8.5 LBS
RESPONSE TIME :	250 ms
FLUID MEDIA :	LH2
OP. PRESS.(psia):	0 TO 45
OP. TEMP. (F deg):	-400 to -422
DENS.(#/ft**3)(H/L):	4.34 / 4.34
FLOWRATE(#/s)(H/L):	2.63 / 0.26
PRESS. DROP(psi)(H/L) :	≤ 5
LEAKAGE ,EXT(sccs of GHe):	1×10^{-4}
MATERIALS OF CONSTRUCTION :	ALUMINUM ALLOY OR TITANIUM ALLOY
COMMENTS: FAIL SAFE CLOSED ON LOSS OF POWER	
LINE SIZE :	2.50 O.D.
LEAKAGE,INT(sccs of GHe):	10 @ 90 psia
CYCLE LIFE(Min):	500



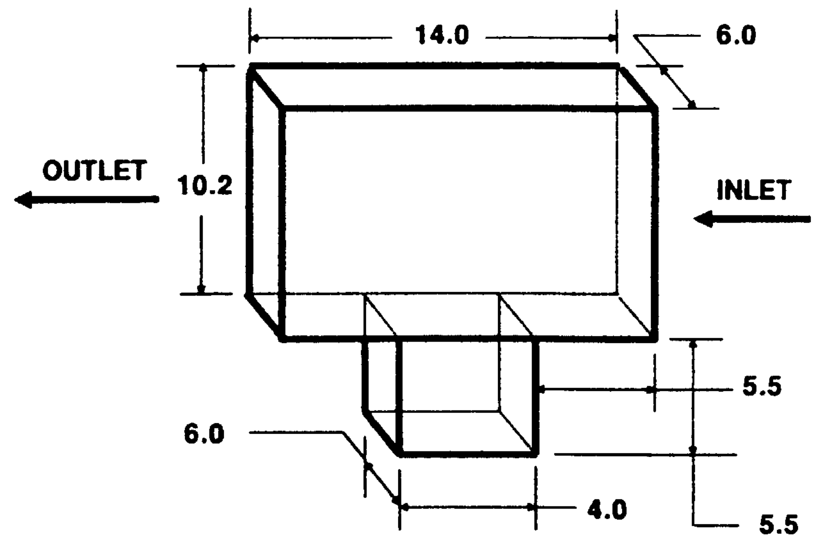
SHUT-OFF VALVE

Figure B-4

VALVE FUNCTION :	OX MAIN SHUT-OFF
VALVE TYPE :	N.C.,ON/OFF,BALL;BFLY;BLADE
ACTUATION METHOD :	28 VDC MOTOR
EST. POWER REQ. :	160 WATTS
EST. WT. (+-20%):	8.0 LBS
RESPONSE TIME :	250 ms
FLUID MEDIA :	LO2
OP. PRESS.(psia):	0 TO 45 PSIA
OP. TEMP. (F deg):	-298
DENS.(#/ft**3)(H/L):	71.2 / 71.2
FLOWRATE(#/s)(H/L):	16.24 / 1.45
PRESS. DROP(psi)(H/L) :	≤ 5
LEAKAGE ,EXT(sccs of GHe):	1×10^{-4}
MATERIALS OF CONSTRUCTION :	ALUMINUM ALLOY

COMMENTS : FAIL SAFE CLOSED ON LOSS OF POWER

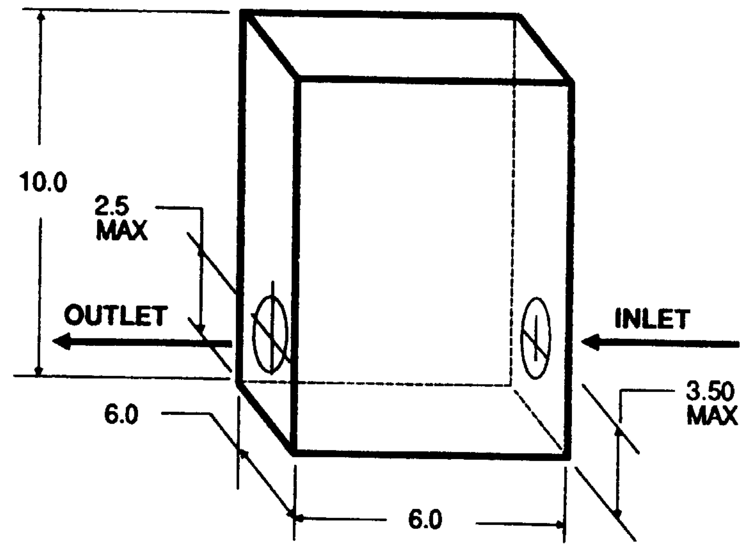
LINE SIZE :	2.25 O.D.
LEAKAGE,INT(sccs of GHe):	10 @ 90 psia
CYCLE LIFE(Min):	500



SHUT-OFF VALVE

Figure B-5

VALVE FUNCTION :	OX TURBINE BYPASS
VALVE TYPE :	SERVO/PINTLE
ACTUATION METHOD :	28 VDC MOTOR
EST. POWER REQ. :	60 WATTS
EST. WT. (+-20%):	9.2 LBS
RESPONSE TIME :	100 ms
FLUID MEDIA :	WARM GO_2
OP. PRESS.(psia)(H/L):	4937 / 330
OP. TEMP. (F deg)(H/L):	400 /400
DENS.(#/ft**3)(H/L):	15.5 / 1.14
FLOWRATE(#/s)(H/L):	13.0 / 1.06
PRESS. DROP(psi)(H/L) :	2290 / 100
LEAKAGE ,EXT(sccs of GHe)	1×10^{-4}
MATERIALS OF CONSTRUCTION :	INCONEL 718 AND OR MONEL 400
COMMENT :	VALVE FAILS IN PLACE
LINE SIZE :	.750 O.D.
OPERATIONAL LIFE(Hrs):	20



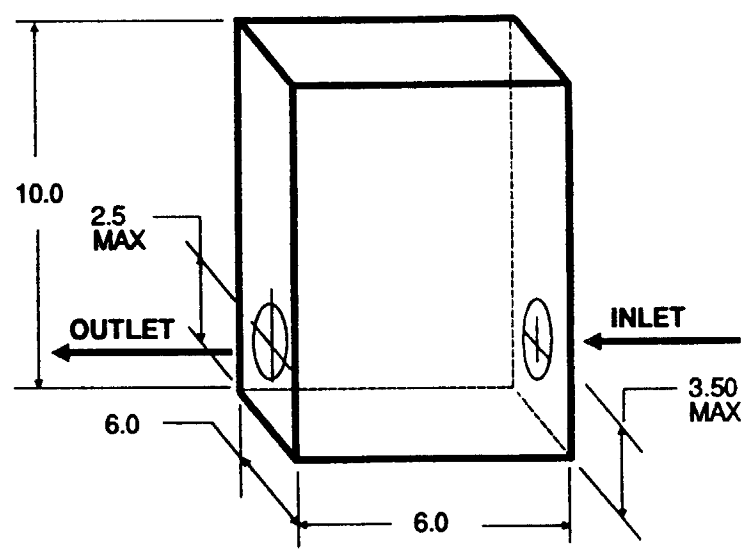
MODULATING VALVE

Figure B-6

VALVE FUNCTION :	HYDROGEN TURBINE BYPASS
VALVE TYPE :	SERVO/PINTLE
ACTUATION METHOD :	28 VDC MOTOR
EST. POWER REQ. :	60 WATTS
EST. WT. (+-20%):	9.2 LBS
RESPONSE TIME :	100 ms
FLUID MEDIA :	HOT GH2
OP. PRESS.(psia)(H/L):	4889 / 298
OP. TEMP. (F deg)(H/L):	540 / 818
DENS.(#/ft**3)(H/L):	0.83 / 0.40
FLOWRATE(#/s)(H/L):	0.3 / 0.16
PRESS. DROP(psi)(H/L) :	2210 / 48
LEAKAGE EXT.(sccs of GHe):	1×10^{-4}
MATERIALS OF CONSTRUCTION :	STAINLESS STEEL OR

INCONEL 718 COMMENT : VALVE FAILS IN PLACE

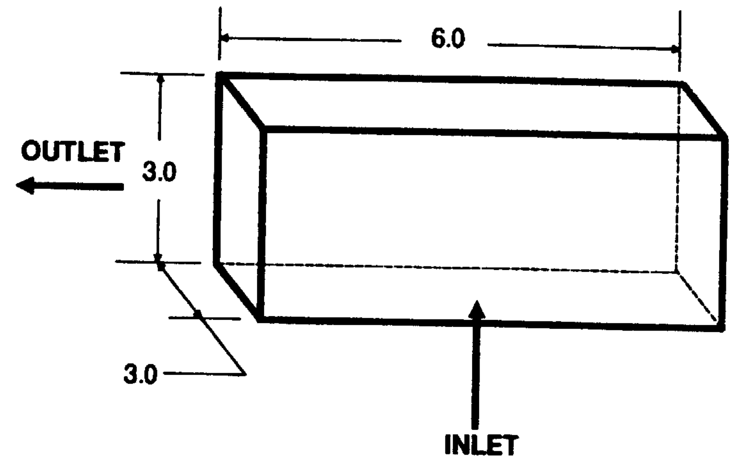
LINE SIZE :	.750 O.D.
OPERATIONAL LIFE(Hrs)	20



MODULATING VALVE

Figure B-7

VALVE FUNCTION :	OX TANK PRESSURIZATION
VALVE TYPE :	N.C.,ON/OFF,POPPET
ACTUATION METHOD :	28 VDC SOLENOID
EST. POWER REQ. :	25 WATTS
EST. WT. (+-20%):	2.60 LBS
RESPONSE TIME :	200 ms
FLUID MEDIA :	GO2
OP. PRESS.(psia):	0 to 3000
OP. TEMP. (F deg):	0 to 400
DENS.(#/ft**3)(H/L):	9.77 / .84
FLOWRATE(#/s)(H/L):	1.66 / .141
PRESS. DROP(psi)(H/L) :	2585 / 215
LEAKAGE , EXT(sccs of GHe):	1 X 10^{-4}
MATERIALS OF CONSTRUCTION :	INCONEL 718 OR MONEL 400
LINE SIZE :	.375 O.D.
CYCLE LIFE(Min):	TBD



TANK PRESSURIZATION

Figure B-8

VALVE FUNCTION :	HYDROGEN TANK PRESSURIZATION
VALVE TYPE :	N.C.,ON/OFF,POPPET
ACTUATION METHOD :	28 VDC SOLENOID
EST. POWER REQ. :	25 WATTS
EST. WT. (+-20%):	2.60 LBS
RESPONSE TIME :	200 ms
FLUID MEDIA :	GH2
OP. PRESS.(psia):	0 to 5000
OP. TEMP. (F deg):	0 to 800
DENS.(#/ft**3)(H/L):	0.49 / 0.04
FLOWRATE(#/s)(H/L):	.375 / .031
PRESS. DROP(psi)(H/L) :	2620 / 220
LEAKAGE ,EXT(sccs of GHe):	1×10^{-4}
MATERIALS OF CONSTRUCTION :	STAINLESS STEEL OR INCONEL 718
LINE SIZE :	.375 O.D.
CYCLE LIFE(Min):	TBD

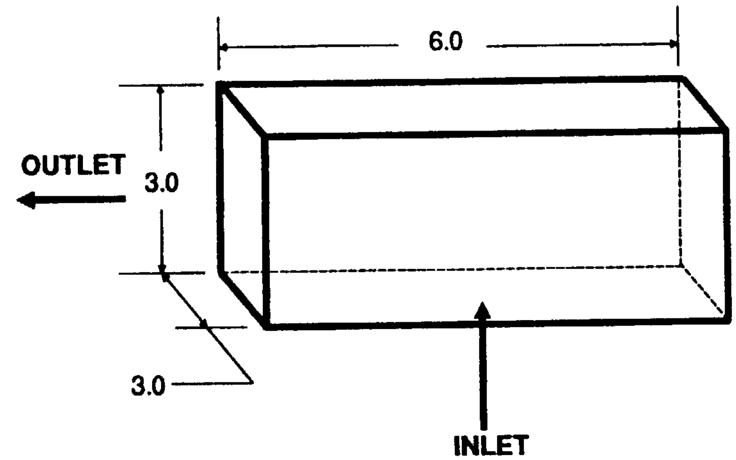
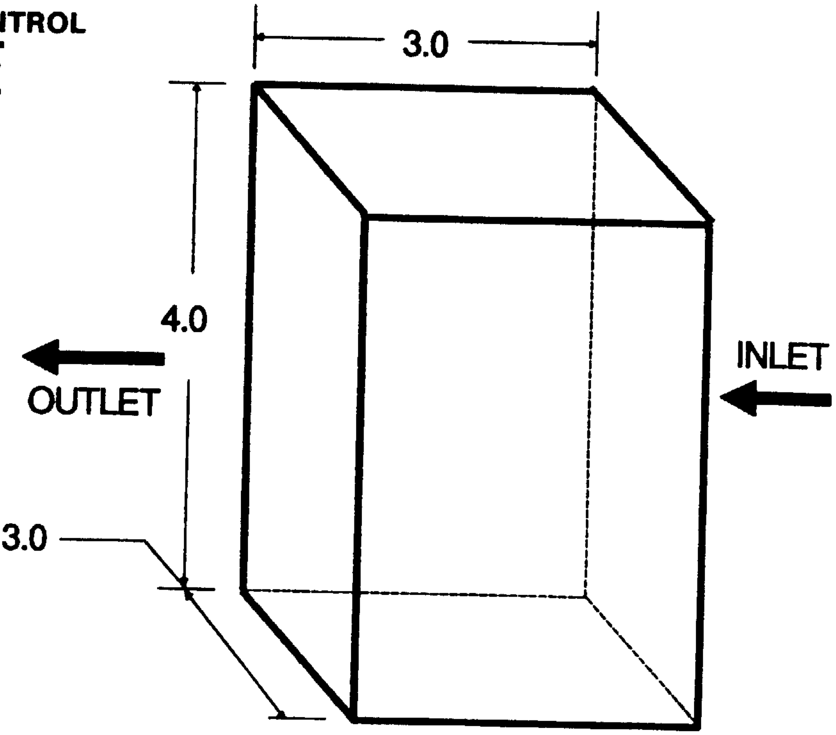


Figure B-9

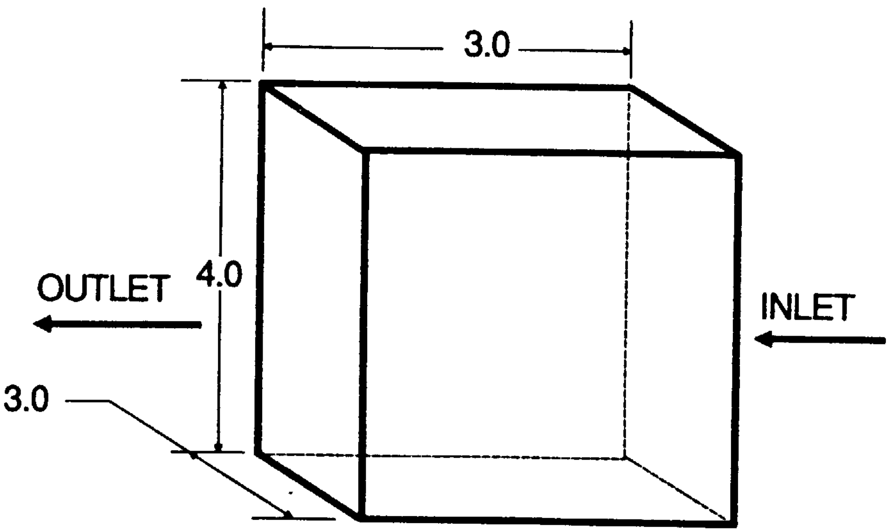
VALVE FUNCTION :	HYDROGEN IGNITER CONTROL
VALVE TYPE :	N.C., OPEN/CLOSE,POPPET
ACTUATION METHOD :	28 VDC SOLENOID
EST. POWER REQ. :	24 WATTS
EST. WT. (+-20%):	1 LB
RESPONSE TIME :	20 ms
FLUID MEDIA :	GH2
OP. PRESS.(psia):	0-6000
OP. TEMP. (F deg):	-400 to 100
DENS.(#/ft**3)(H/L):	71.2 / 71.2
FLOWRATE(#/s)(H/L):	.040 / .0035
PRESS. DROP(psi)(H/L) :	TBS / TBS
LEAKAGE ,EXT(sccs of GHe):	1×10^{-4}
MATERIALS OF CONSTRUCTION :	S.S.
LINE SIZE :	.250 O.D.
CYCLE LIFE(Min):	500



IGNITER VALVES

Figure B-10

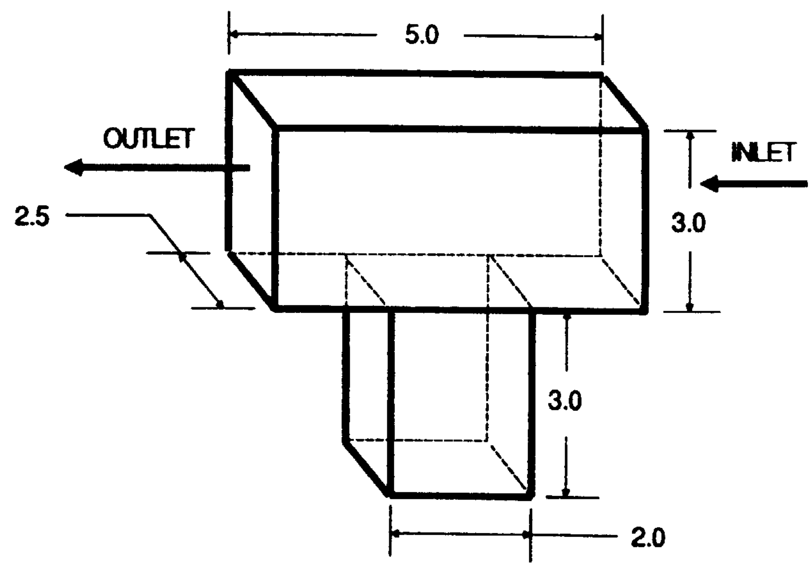
VALVE FUNCTION :	OX IGNITER CONTROL
VALVE TYPE :	N.C.,OPEN/CLOSED,POPPET
ACTUATION METHOD :	28 VDC SOLENOID
EST. POWER REQ. :	24 WATTS
EST. WT. (+-20%):	1 LB
RESPONSE TIME :	20 ms
FLUID MEDIA :	GO2
OP. PRESS.(psia):	0 -6000
OP. TEMP. (F deg):	-400 to 100
DENS.(#/ft**3)(H/L):	4.50/4.49
FLOWRATE(#/s)(H/L):	.145 / .0125
PRESS. DROP(psi)(H/L) :	TBS / TBS
LEAKAGE ,EXT(sccs of GHe):	1 X 10^{-4}
MATERIALS OF CONSTRUCTION :	MONEL 400 OR INCONEL 718
LINE SIZE :	.250 O.D.
CYCLE LIFE(Min):	500



IGNITER VALVE

Figure B-11

VALVE FUNCTION :	HYDROGEN IDLE
VALVE TYPE :	PRESSURE BALANCE, OPEN/PARTIAL CLOSE
ACTUATION METHOD*:	LINE PRESSURE
EST. POWER REQ. :	N/A
EST. WT. (+-20%):	5.0 LBS
RESPONSE TIME :	250 ms
FLUID MEDIA :	GH2
OP. PRESS.(psia):	80 psid ACTUATE, 0 to 6000 psia
OP. TEMP. (F deg):	-360 to 540
DENS.(#/ft**3)(H/L):	.04
FLOWRATE(#/s)(H/L):	0.0 TO .26
PRESS. DROP(psi)(H/L) :	0.0 to 80
LEAKAGE ,EXT(sccs of GHe):	1×10^{-4}
MATERIALS OF CONSTRUCTION :	STAINLESS STEEL
LINE SIZE :	1.00 O.D.
OPERATIONAL LIFE(Hrs):	20



HYDROGEN IDLE VALVE

*THIS IS AN ALTERNATE VALVE SHOULD MIXTURE RATIO CONTROL ON STARTUP PROVE CRITICAL AND REQUIRE A MODULATING VALVE.

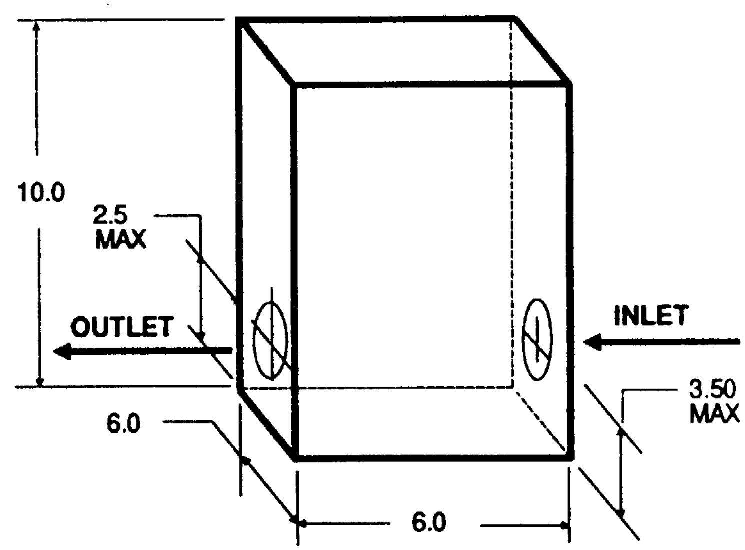
Figure B-12

VALVE FUNCTION :	HYDROGEN REGEN, BYPASS
VALVE TYPE :	MODULATING POPPET
ACTUATION METHOD :	28 VDC MOTOR
EST. POWER REQ. :	60 WATTS
EST. WT. (+-20%):	9.2 LBS
RESPONSE TIME :	100 ms
FLUID MEDIA :	H2
OP. PRESS.(psia)(H/L)	5580 / 390
OP. TEMP. (F deg)(H/L)	-340 / -420
DENS.(#/ft**3)(H/L):	4.50 / 4.49
FLOWRATE(#/s)(H/L):	0.53 / 0.26
PRESS. DROP(psi)(H/L) :	75 / 5
LEAKAGE ,EXT(sccs of GHe)	1×10^{-4}
MATERIALS OF CONSTRUCTION :	ALUMINUM ALLOY

OR TITANIUM ALLOY

COMMENT : VALVE MUST FAIL OPEN

LINE SIZE :	1.00 O.D.
OPERATIONAL LIFE(Hrs):	20

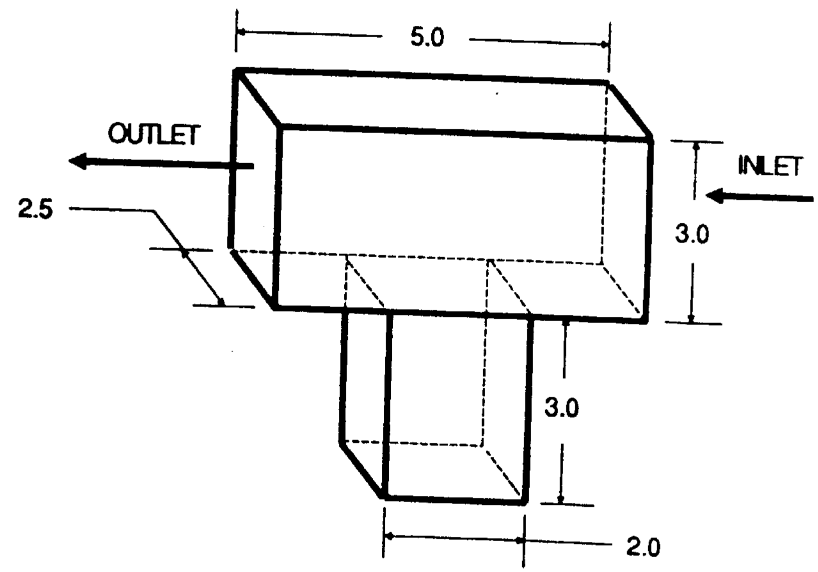


MODULATING VALVE

Figure B-13

VALVE FUNCTION : HYDROGEN IDLE
VALVE TYPE : PRESSURE BALANCE, OPEN/PARTIAL CLOSE
ACTUATION METHOD*: LINE PRESSURE
EST. POWER REQ. : N/A
EST. WT. (+-20%): 5.0 LBS
RESPONSE TIME : 250 ms
FLUID MEDIA : GH2
OP. PRESS.(psia): 80 psid ACTUATE, 0 to 6000 psia
OP. TEMP. (F deg): -360 to 540
DENS.(#/ft**3)(H/L): .04
FLOWRATE(#/s)(H/L): 0.0 TO .26
PRESS. DROP(psi)(H/L) : 0.0 to 80
LEAKAGE ,EXT(sccs of GHe): 1 X 10^{-4}
MATERIALS OF CONSTRUCTION : STAINLESS STEEL

LINE SIZE : 1.00 O.D.
OPERATIONAL LIFE(Hrs): 20



HYDROGEN IDLE VALVE

Figure B-14

VALVE FUNCTION :	HYDROGEN BACK PRESSURE
VALVE TYPE :	N.C., OPEN/PARTIAL CLOSED ,POPPET
ACTUATION METHOD :	LINE PRESSURE
EST. POWER REQ. :	N/A
EST. WT. (+-20%):	3.0 LBS
RESPONSE TIME :	250 ms @ 500 psia
FLUID MEDIA :	GH2
OP. PRESS.(psia):	0 to 4889
OP. TEMP. (F deg):	50 to 818
DENS.(#/ft**3)(H/L):	0.83 / 0.04
FLOWRATE(#/s)(H/L):	2.63 / 0.26
PRESS. DROP(psi)(H/L) :	10.0 / 2.2
LEAKAGE ,EXT(sccs of GHe):	1×10^{-4}
MATERIALS OF CONSTRUCTION :	INCONEL 718 OR STAINLESS STEEL
LINE SIZE :	1.25 O.D.
CYCLE LIFE(Min):	500

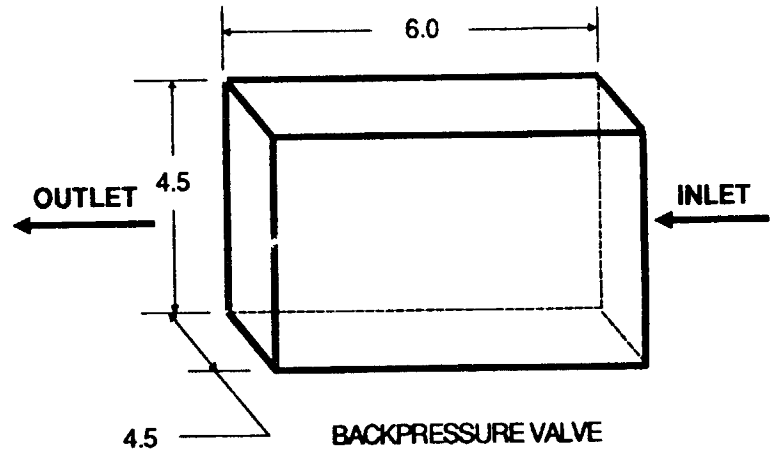
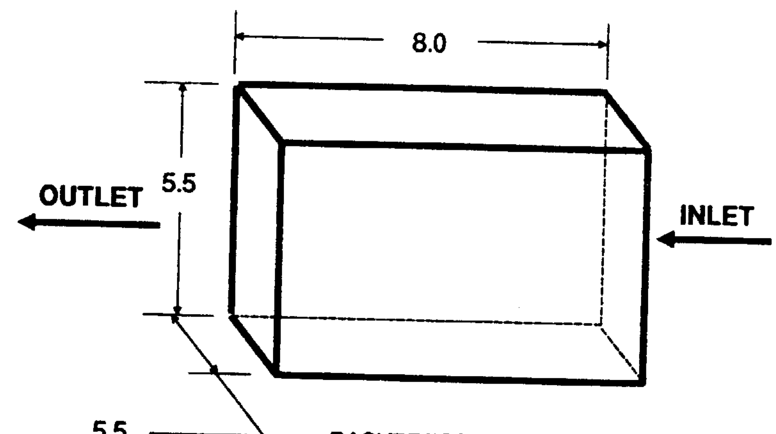


Figure B-15

VALVE FUNCTION :	OX BACKPRESSURE
VALVE TYPE :	N.C., OPEN/PARTIAL CLOSED, POPPET
ACTUATION METHOD :	LINE PRESSURE
EST. POWER REQ. :	N/A
EST. WT. (+-20%):	5.0 LBS
RESPONSE TIME :	250 ms @ 500psia
FLUID MEDIA :	GO2
OP. PRESS.(psia):	0 to 4937
OP. TEMP. (F deg):	-260 to 400
DENS.(#/ft**3)(H/L):	15.5 / 1.14
FLOWRATE(#/s)(H/L):	16.24 / 1.45
PRESS. DROP(psi)(H/L) :	22.0 / 2.4
LEAKAGE ,EXT(sccs of GHe):	1×10^{-4}
MATERIALS OF CONSTRUCTION :	INCONEL 718 OR MONEL 400
LINE SIZE :	1.75 O.D.
CYCLE LIFE(Min):	500



BACKPRESSURE VALVE

Figure B-16

Table B-1.
Health Monitor and Control Sensor List

Component	Sensor	Location	Function: Control	HM-1	HM-2	Wt.	PWR.
Hydrogen Turbopump Assy.	Z1 Shaft Axial Displ.	Inside First Stage Turbo-pump Assy.		X			
	Z2 Shaft Radial Displ.			X		2.5 for 3 Functions	10 VDC 30MA for 3 Functions
	S1 Speed			X			
	Z3 Shaft Axial Displ.	Inside First Stage Turbo-pump Assy. 90° from Z1		X			
	Z4 Shaft Radial Displ.			X		2.5 for 3 Functions	10 VDC 30MA for 3 Functions
	S2 Speed				X		
	P-1 Pump Discharge Pres.	To Line @ Pump Disch.	XX			0.5 Oz.	10 VDC 15MA
	T-1 Pump Discharge Temp.	To Line @ Pump Disch.	XX			0.7 Oz.	10 VDC 15MA
	F-1 Pump Flow		XX			12 Oz.	28 VDC 20MA
	Z5 TPA Vibration	On T-P Housing Between Brgs.		X		.07 Oz.	15 VDC 4MA
Hydrogen Turbopump Assy.	Z6 Shaft Axial Displ.	Inside 2nd Stage Turbo-pump Assy.		X			
	Z7 Shaft Radial Displ.			X		2.5 Oz. for 3 Functions	10 VDC 30MA for 3 Functions
	S3 Speed			X			
	Z8 Shaft Axial Displ.	Inside 2nd Stage Turbo-pump Assy. 90° from Z3		X			
	Z9 Shaft Radial Displ.			X		2.5 Oz. for 3 Functions	10 VDC 30MA for 3 Functions
	S4 Speed				X		
	P2 Pump Interstage Pres.	To TPA Between Stages			X	0.5 Oz.	10 VDC 15MA
	T2 Pump Interstage Temp.	On TPA Between Stages			X	0.7 Oz.	10 VDC 15MA
	P3 Turbine 2nd Stage Inlet Pres.	On TP Housing Between Stages			X	0.5 Oz.	10 VDC 15MA
	T3 Turbine 2nd Stage Inlet Temp.				X	0.3 Oz.	10 VDC 15MA

Table B-1.
Health Monitor and Control Sensor List (Cont.)

Component	Sensor	Location	Function			Wt.	PWR.
			Control	HM-1	HM-2		
Hydrogen Turbopump Assy.	P4 Pump Inlet Pres.	In Line @ Pump Inlet			X	0.5 Oz.	10 VDC 15MA
	P5 Turbine Inlet Pres.	In Line @ Turbine Inlet		X			
	P6 Turbine Disch Pres.	In Line @ Turbine Outlet			X		
	T4 Turbine Inlet Temp.	In Line @ Turbine Inlet	XX			0.7 Oz.	10 VDC 15MA
	T5 Turbine Disch. Temp	In Line @ Turbine Disch.			X	0.7 Oz.	10 VDC 15MA
	F2 Turbine Inlet Flow	In Line @ Turbine Inlet			X	12 Oz.	28 VDC 20MA
	T6 Pump Inlet Temp.	In Line @ Pump Inlet			X	0.7 Oz.	10 VDC 15MA
Hydrogen Boost Turbo-pump. Assy.	Z10 Bearing Outer Race Deflectometer	On Bearing Outer Race .005 In. Nominal Clearances		X		0.8 Oz.	10V 20MA for 2 Sensors
	Z11 Bearing Outer Race Deflectometer			X		0.8 Oz.	2 Sensors
	Z12 Boost Pump Accel.	On Boost Pump Housing Be-tween Brgs.			X	0.07 Oz.	15 VDC 4MA
	P7 Boost Pump Inlet Pres.	In Line @ Pump Inlet			X	0.5 Oz.	10 VDC 15MA
	T-7 Boost Pump Inlet Temp.	In Line @ Pump Inlet			X	0.7 Oz.	10 VDC 15MA
	F3 Boost Turbine Inlet Flow	In Line @ Turbine Inlet			X	12 Oz.	28 VDC 20MA
Oxygen Turbopump Assy.	Z13 Shaft Axial Displ.	Inside Turbo-pump Assy.		X			
	Z14 Shaft Radial Displ.			X		2.5 Oz. for 3 Functions	10 VDC 30MA for 3 Functions
	S5 Speed			X			
	Z15 Shaft Axial Displ.	Inside Turbo-pump Assy. 90° from Z5		X			
	Z16 Shaft Radial Displ.			X		2.5 Oz. for 3 Functions	10 VDC 30MA for 3 Functions
	S6 Speed				X		

Page 2 of 5

Table B-1.
Health Monitor and Control Sensor List (Cont.)

Component	Sensor	Location	Function: Control	HM-1	HM-2	Wt.	PWR.
Oxygen Turbopump Assy.	P8 Pump Disch. Pres.	In Line @ Pump Disch.	XX			0.5 Oz.	10 VDC 15MA
↓	T7 Pump Disch. Temp.	In Line @ Pump Disch.	XX			0.7 Oz.	10 VDC 15MA
↓	F4 Pump Flow	↓	XX			12 Oz.	28 VDC 20MA
↓	Z17	On T.P. Housing Between Bearings		X		0.07 Oz.	15 VDC 4MA
Oxygen Turbopump Assy.	P9 Pump Inlet Pres.	In Line @ Pump Inlet			X	0.5 Oz.	10 VDC 15MA
↓	P10 Turbine Inlet Pres.	In Line @ Turbine Inlet		X		↓	↓
↓	T8 Turbine Inlet Temp.	In Line @ Turbine Inlet	XX			0.7 Oz.	10 VDC 15MA
↓	T9 Turbine Disch. Temp.	In Line @ Turbine Disch.			X	0.7 Oz.	↓
↓	T10 Pump Inlet Temp.	In Line @ Pump Inlet			X	0.7 Oz.	↓
↓	F5 Turbine Inlet Flow	In Line @ Turbine Inlet			X	12 Oz.	28 VDC 20MA
Oxygen Boost Turbo-pump Assy.	Z18 Bearing Outer Race Deflectometer	On Bearing Outer Race .005 In. Nominal Clearance		X		0.8 Oz.	28 VDC 20MA for 2 Sensors
↓	Z19 Bearing Outer Race Deflectometer	↓		X		↓	↓
↓	Z20 Boost Pump Accel.	On Boost Pump Hsg. Between Brgs.			X	.07 Oz.	15 VDC 4MA
↓	P11 Boost Pump Inlet Pres.	In Line @ Pump Inlet Thermal Isolation Req'd by Tube Conn.			X	0.5 Oz.	10 VDC 15MA
↓	T11 Boost Pump Inlet Temp.	In Line @ Pump Inlet			X	.7 Oz.	10 VDC 15MA
↓	F6 Boost Turbine Inlet Flow	In Line @ Turbine Inlet			X	.12 Oz.	28 VDC 20MA
Combustion Chamber	P12 Chamber Pressure	Combustion Chamber	XX			0.5 Oz.	10 VDC 15MA

Table B-1.
Health Monitor and Control Sensor List (Cont.)

Component	Sensor	Location	Function			Wt.	PWR.
			Control	HM-1	HM-2		
Injector	P13 Fuel Inlet Pressure	At Injector Fuel Inlet		X		0.3 Oz.	10 VDC 15MA
↓	T12 Fuel Inlet Temp.	↓		X		0.7 Oz.	↓
↓	P14 Oxidizer Inlet Pressure	At Injector Oxidizer Inlet		X		0.5 Oz.	↓
↓	T13 Oxidizer Inlet Temp.	↓		X		0.7 Oz.	↓
Combustion Chamber	P15 Chamber Coolant Outlet Pres.	At Chamber Coolant Outlet		X		0.5 Oz.	↓
↓	T14 Chamber Coolant Outlet Temp.	↓		X		0.7 Oz.	↓
↓	P16 Chamber Baffle Coolant Outlet Pres.	At Transition Between Chamber Baffle Coolant			X	0.5 Oz.	↓
↓	T15 Chamber Baffle Coolant Outlet Temp.	↓			X	0.7 Oz.	↓
↓	T16 Chamber Throat Surface Temp.	Multiple Sensor Band Around Chamber Throat			X	TBD	TBD
Nozzle	P17 Fuel Coolant Inlet Pres.	At Nozzle Fuel Inlet Manifold		X		0.5 Oz.	10 VDC 15MA
↓	T17 Fuel Coolant Inlet Temp.	↓		X		0.7 Oz.	↓
↓	P18 Ox. Coolant Inlet Pres.	At Nozzle Ox. Inlet Manifold		X		0.5 Oz.	↓
↓	T18 Ox. Coolant Inlet Temp.	↓		X		0.7 Oz.	↓
↓	P19 Ox. Coolant Outlet Pres.	At Nozzle Ox. Outlet Manifold			X	0.5 Oz.	↓
↓	T19 Ox. Coolant Outlet Temp.	↓			X	0.7 Oz.	↓
Regen	T20 Fuel Regen Outlet Temp.	@ Fuel Regen Sec. Outlet Port.		X		0.7 Oz.	↓
↓	T21 Ox. Regen Fuel Inlet Temp.	Ox. Regen Inlet Port			X	0.7 Oz.	↓
↓	P20 Fuel Regen Inlet Pres.	Fuel Regen Inlet Port			X	0.5 Oz.	↓

Table B-1.
Health Monitor and Control Sensor List (Cont.)

Component	Sensor	Location	Function			Wt.	PWR.
			Control	HM-1	HM-2		
Fuel Turbine Bypass Valve	Z21 Position	On Valve Pintle Extension	XX			3.2 Oz. for 1 In. Stroke	28 VDC 20MA
Ox. Turbine Bypass Valve	Z22 Position		XX				
Hex. Bypass Valve	Z23 Position		XX				
Fuel Idle Valve	Z24 Position		XX				
Fuel Regen, Bypass Valve	Z25 Position		XX				
Nozzle Position	Z26 Position-Ret. Z27 Position-Ext.	Limit Switches at Limits of Travel	XX			0.3 Oz.	28 VDC 1MA
Engine Compartment	T22, T23, T24, T25 Temperature	In Engine Compartment 4 Places		X		0.02 Oz.	10 VDC 15MA
Engine Compartment	L1, L2, L3, L4 H2 Leak Detection	In Engine Compartment 4 Places		X		TBD	TBD
Engine Compartment	L5, L6, L7, L8 O_2 Leak Detection	In Engine Compartment 4 Places		X			
Total			16 + 16	46	31		

APPENDIX C

OTV ENGINE FAILURE MODES AND EFFECTS ANALYSIS

OTV DUAL PROPELLANT EXPANDER CYCLE ENGINE
FAILURE MODES AND EFFECTS ANALYSIS

COMPONENT OR SUBSYSTEM	FAILURE MODE	SYSTEM EFFECT	SYSTEM FAILURE FULL	SYSTEM FAILURE PARTIAL
Propellant Inlet Shutoff Valves (LO_2/LH_2)	1. 1 unit fails to close.	1. No effect - series redundant.		
(Series redundant/one valve on each side of interface)	2. Both units fail to close.	2. No effect - close tank isolation valve.		X
	3. 1 or 2 unit(s) fail to open.	3. No engine operation W/O EVA and manual operation of valve.	X	
	4. 1 unit fails partially open or closed.	4. Engine may operate at partial thrust but can still be throttled, started, shutdown.		X
	5. Response time out of tolerance	5. No effect on closing (series redundant). No effect on opening due to to (relatively) long start time operation (tank head idle mode).		
Oxidizer Turbopump Assembly	1. Loss of LO_2 to hydrostatic bearings (contamination).	1. Bearings have redundant lubrication passages - partial loss may result in bearing wear. Significant or total loss may cause ignition or melting and HM directed shutdown. (Pump surfaces can tolerate rubbing friction for TBD msec without catastrophic failure).	X	X
	2. Cavitation or bubble/gas ingestion due to blocked or restricted inlet (contamination, or partial inlet valve failure, or failure in propellant acquisition system.)	2. Reduced pump life, reduced thrust. HM directed shutdown due to pump overspeed. Restart is possible if overspeed did not reach design limit.	X	X

OTV DUAL PROPELLANT EXPANDER CYCLE ENGINE
FAILURE MODES AND EFFECTS ANALYSIS

COMPONENT OR SUBSYSTEM	FAILURE MODE	SYSTEM EFFECT	SYSTEM FAILURE FULL	PARTIAL
	3. Turbine blade cracks, failure, or damage.	3. HM directed shutdown or reduced thrust operation.	X	X
Fuel Turbopump Assembly	1. Loss of LH_2 to hydrostatic bearings (contamination).	1. Bearings have redundant lubrication passages-partial loss may result in bearing wear, reduced pump life. Total loss will result in pump failure.		X
	2. Cavitation or bubble/ingestion due to blocked or restricted inlet (contamination or partial inlet valve failure or failure in propellant acquisition system).	2. Reduced pump life, reduced thrust. HM directed shutdown due to pump overspeed. Restart is possible if overspeed did not reach design limit.	X	X
	3. Turbine blade cracks, failure, or damage.	3. HM directed shutdown or reduced thrust operations.	X	X
Oxidizer Boost Pump	1. Pump fails to operate.	1. Requires tank head start - questionable reliability	Uncertain	
<u>Concept A</u>: Individual boost pumps for each OTV engine. <u>Concept B</u>: 2 ea. boost pumps feeding engine cluster inlet manifold.	2. Pump operates at reduced flow or pressure.	2. Engine MR, thrust, Isp are effected.		X
	3. 1 pump to operate or operates at reduced flow or pressure.	3. No effect - parallel redundant.		
	4. Both pumps fail to operate.	4. It successfully started on tank head pressure autogenous system will give normal operation.	Uncertain	

OTV DUAL PROPELLANT EXPANDER CYCLE ENGINE
FAILURE MODES AND EFFECTS ANALYSIS

COMPONENT OR SUBSYSTEM		FAILURE MODE		SYSTEM EFFECT	SYSTEM FAILURE FULL	SYSTEM FAILURE PARTIAL
High Pressure Pump Discharge Line(s)	1.	Leaks or cracks at lines, seals, or joints.	1.	Engine operates off MR. Lowr thrust and Isp		X
Hydrogen system only	2.	Catastrophic structural failure or rupture.	2.	Engine fails to opeate due to insufficient fuel.	X	
Oxygen system only	3.	Catastrophic structural failure.	3.	Possible fire, low order explosion.	X	
Igniter System	1.	1 unit fails to operate.	1.	No effect - fully redundant system.		
(Dual-redundant spark gap type elements. Inductive ignition coils, and electronics - may utilize hydrogen cooled ceramic element in lieu of igniter valves.)	2.	Both units fail to operate.	2.	No engine ignition.	X	
	3.	Spark delay on startup.	3.	Pressure spike and HM directed engine shutdown.	X	
Oxygen Turbine Bypass Valve	1.	Valves fail to open, close, or partially operate; or response time out of limits.	1.	Loss of throttling capability on affected engine. In multiple engine concept, other engines can gimbal and/or throttle to correct or null thrust vector. Health monitoring system can detect valve operational failure and adjust fuel throttling valve(s) to prevent catastrophic MR and resulting TCA damage.		X
	2.	Valve surfaces have rubbing contact or fretting.	2.	Possible ignition depending on magnitude and duration of friction. HM directed engine shutdown.	X	TBD

OTV DUAL PROPELLANT EXPANDER CYCLE ENGINE
FAILURE MODES AND EFFECTS ANALYSIS

COMPONENT OR SUBSYSTEM	FAILURE MODE	SYSTEM EFFECT	SYSTEM FAILURE FULL	SYSTEM FAILURE PARTIAL
	3. Valve has internal leakage.	3. Magnitude of leakage may affect throttling capability and MR.		X
Hyrogen Turbine	1. Valve fails to open, close, or partially operate; or response time out of limits.	1. Loss of throttling capability on affected engine. In multiple engine concept, other engines can gimbal and/or throttle to correct or null thrust vector. Health monitoring system can detect valve operational failure and adjust oxidizer bypass valve to prevent catastrophic MR and resulting TCA damage.		X
	2. Valve has internal and/or external leakage.	2. Magnitude of leakage may affect throttling capability and MR, reduced Isp.		X
	3. Failure of valve actuating coil control.	3. No effect. Redundant operating coils/ controls.		
Thrust Chamber Assembly	1. Leaks or cracks on TCA inner walls.	1. System may operate off MR, reduced thrust and Isp.		X
	2. Leaks or cracks on TCA outer walls.	2. System operates off MR, reduced thrust and Isp. Shutdown if leak detection system is installed.	X	X
	3. Major rupture or substantial foreign object damage.	3. Engine shutdown by HM system.	X	
	4. Plugged cooling channels (contamination).	4. May reduce engine life, otherwise no effect on performance.		X

OTV DUAL PROPELLANT EXPANDER CYCLE ENGINE
FAILURE MODES AND EFFECTS ANALYSIS

COMPONENT OR SUBSYSTEM	FAILURE MODE	SYSTEM EFFECT	SYSTEM FAILURE FULL	SYSTEM FAILURE PARTIAL
Baffle Plate	1. Burn through in outer wall.	1. May affect MR, Isp depending on magnitude.		X
	2. Plugged cooling channels (contamination).	2. May reduce baffle life - otherwise no effect on performance.		X
Injector	1. Plugged orifices (contamination).	1. May affect MR, Isp, thrust. Worst case (loss of fuel film cooling) may result in reduced engine life (thermal limits exceeded) or could cause TCA burn through. HM directed shutdown.	TBD	X
Engine Controller/ Health Monitoring System	1. HM system erroneously predicts engine/system, component degradation or failure.	1. Engine operates at lower thrust, Isp, or off MR. May be directed to shutdown.	X	X
<u>Concept A</u>: Supervisory or limited control.	2. Controller fails to adjust engine operation based on actual (non-catastrophic fault).	2. Reduced engine life. May cause HM directed shutdown.	X	X
<u>Concept B</u>: Full authority control (redundant multiple channel).	3. Partial faiure of controller, or loss of instrumentation parameter.	3. No effect - controller is redundant channel, can synthesize missing parameter or substitute nominal performance value.		
	4. Total failure of controller or instrumentation group.	4. Loss of engine operation. Propellant shut-off valves close.	X	

OTV DUAL PROPELLANT EXPANDER CYCLE ENGINE
FAILURE MODES AND EFFECTS ANALYSIS

COMPONENT OR SUBSYSTEM	FAILURE MODE	SYSTEM EFFECT	SYSTEM FAILURE FULL	SYSTEM FAILURE PARTIAL
Instrumentation Transducer	1. Transducer fails totally, calibration shifts, or transducer gives incorrect readings and/or transients.	1. No effect - health monitoring system can synthesize parameter or substitute nominal performance value. Most transducers will be redundant dual element design; health monitoring system can "vote out" incorrect reading by reate-of-change transient computations (transducer drop outs or erratic transients) and by coparison with other combustion transducer parameters.	No effect	
Gimbal System	1. Gimbal actuators fail to extend or retract, insufficient stroke, erratic operation or slew rate.	1. Unaffected engines (multiple engine scenario) can compensate by selective gimbaling or throttling to null or correct thrust vector.		X
Radiation Cooled Nozzle	1. Burn throughs, coating cracks, structural damage from handling, foreign objects/meteors.	1. Reduced thrust, Isp - otherwise no effect on engine system operation (throttling and/or gimbal system can compensate at system (multiple engine) level in worst case. Possible local heating of aerobrake.		X
Nozzle Retraction	1. Fails to retract.	1. May prevent aerobraking. Jettison if system has that capability.	TBD	
	2. Fails in intermediate position.	2. May prevent aerobraking. Jettison if system has that capability.	TBD	
Nozzle Extension	1. Fails to extend.	1. Engine can be operated. No gimbal capability. Some local heating of aerobrake.		X

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CR182122		

4. Title and Subtitle	
Integrated Control and Health Management Phase II Task Final Report, Orbit Transfer Rocket Engine Technology Program	5. Report Date: July 1988
	6. Performing Organization Code
7. Author(s): Wilfried A. Holzmann, Warren R. Hayden	8. Performing Organization Report No.: ATC 2459-42-1
	10. Work Unit No.: 506-42-21 52583
9. Performing Organization Name and Address: Aerojet TechSystems Company, P.O. Box 13222, Sacramento, CA 95813	11. Contract or Grant No.: NAS 3-23772
	13. Type of Report and Period Covered: Contractor Report Final
12. Sponsoring Agency Name and Address: NASA Lewis Research Center, Cleveland, Ohio 44135	14. Sponsoring Agency Code

15. Supplementary Notes
NASA LeRC Task Monitor was Marc G. Millis, (216) 433-2425
Mail Stop 500-220
NASA Lewis Research Center
21000 BrookPark Road
Cleveland, Ohio 44135

16. Abstract
To insure controllability of the baseline design for a 7,500 pound thrust, 10:1 throtteable, dual expander cycle, Hydrogen-Oxygen, orbit transfer rocket engine, an Integrated Controls and Health Monitoring concept was developed. This included: (1) Dynamic engine simulations using a TUTSIM derived computer code, (2) Analysis of various control methods, (3) Failure Modes Analysis to identify critical sensors, (4) Survey of applicable sensors technology, and (5) Study of Health Monitoring philosophies. The engine design was found to be controllable over the full throttling range by using 13 valves, including an oxygen turbine bypass valve to control mixture ratio, and a hydrogen turbine bypass valve, used in conjuction with the oxygen bypass, to control thrust. Classic feedback control methods are proposed along with specific requirements for valves, sensors, and the controller. Expanding on the control system, a Health Monitoring system is proposed including suggested computing methods and the following recommended sensors: (1) Fiber optic and silicon bearing deflectometers, (2) Capacitive shaft displacement sensors, and (3) Hot spot thermocouple arrays. Further work is needed to refine and verify the dynamic simulations and control algorithms, to advance sensor capabilities, and to develop the Health Monitoring computational methods.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Rocket Engine Controls, Health Monitoring, Dual Expander Cycle, Orbit Transfer Vehicle, Advanced Sensors	Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
UNCLASSIFIED	UNCLASSIFIED	136	

*For sale by the National Technical Information Service, Springfield, Virginia 22161